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Research Report

Naval Warfare Research Center

Research Memorandum
NWRC RM-50

NAVAL APPLICATIONS OF MAN-IN-THE-SEA CONCEPTS — MISSION DEFINITION

By: ALBERT BIEN PETER J. McDONOUGH

Prepared for:

OFFICE OF NAVAL RESEARCH
NAVAL ANALYSIS PROGRAMS
DEPARTMENT OF THE NAVY
WASHINGTON, D.C. 20360

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STANFORD RESEARCH INSTITUTE
Menlo Park, California 94025 · U.S.A.

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SRI Project 7000-212

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CONTRACT NO. N00014-68-A-0243

ABSTRACT

Naval undersea missions and operations in the 1975-1985 time frame that require the use of MAN-IN-THE-SEA concepts are delineated. The MAN-IN-THE-SEA concept is broadly defined in this study to include all undersea systems requiring man's exposure to the ambient ocean pressure. MAN-IN-THE-SEA missions and operations within the overall spectrum of naval undersea missions and operations are isolated on the basis of comparisons of functional performance capabilities of alternative systems. The functional requirements related to the naval undersea missions and operations, together with the isolated MAN-IN-THE-SEA missions and operations, are initial results of a continuing study of naval applications of MAN-IN-THE-SEA concepts.

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A study such as the one reported here is made possible by the cooperative support of the military departments and their contractors. Cognizant personnel of the following organizations provided valuable guidance and information essential to the conduct of the study:

Office of Naval Research
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Washington, D.C.

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Ocean Engineering Planning Group
Washington, D.C.

Office of the Supervisor of Salvage
Washington, D.C.

Experimental Diving Unit
Washington, D.C.

U.S. Navy Mine Defense Laboratory
Panama City, Florida

Northrop, Nortronics Division
Palos Verdes Peninsula, California

North American Rockwell
Ocean Systems Operation
Compton, California

U.S. Navy Submarine Medical Center
Medical Research Laboratory
New London, Connecticut

General Dynamics
Electric Boat Division
Groton, Connecticut

Whittenburg, Vaughan, Incorporated
Fairfax, Virginia

Oceanic Institute
Makapuu Point
Waimanalo, Hawaii

U.S. Naval Weapons Center/Undersea Warfare Center
China Lake, California

PREFACE

A study of the naval application of MAN-IN-THE-SEA concepts in the 1975-1985 time frame is being conducted by the Naval Analysis Programs Group, Mr. J. R. Marvin, Director, in the Office of Naval Research. Mr. B. L. Friedman is the ONR Project Scientific Officer. The fundamental objectives of the study are to identify the potential contributions of MAN-IN-THE-SEA capabilities to the accomplishment of naval missions and to provide guidelines for the structuring of a long range MAN-IN-THE-SEA research program. This research memorandum presents the initial results of a continuing study effort. The research effort was performed by the Naval Warfare Research Center of Stanford Research Institute. Mr. A. Bien of the Naval Warfare Research Center was the principal investigator. Mr. P. J. McDonough of the Santa Barbara Analysis and Planning Corporation was the principal subcontractor to the study.

CONTENTS

Contents (continued)

ILLUSTRATIONS

TABLES

Tables (continued)

I INTRODUCTION

A. General

MAN-IN-THE-SEA concepts are defined broadly as those underwater systems where man is exposed to the ambient pressure in the ocean environment. This approach contrasts with those underwater systems in which man is protected from the ambient pressure by (1) placing him in the protective shell of a pressure vessel or (2) locating him on the sea's surface and having him remotely operate underwater equipments.

In recent years, significant advances in the capabilities of MAN-IN-THE-SEA concepts have been realized. These advances, resulting principally from the development of saturation diving techniques, are reflected in the extended depth and time man is able to venture into the sea. The U.S. Navy, recognizing the possible military potentials offered by man's increasing undersea capabilities, is supporting a MAN-IN-THE-SEA program. This program is directed toward developing man's ability to accomplish useful work down to the depth of the continental shelf and determining man's ultimate depth-time limits in the ambient undersea environment. The completed SEALAB I and II and the upcoming SEALAB III operations are one aspect of the total Navy MAN-IN-THE-SEA program.

In light of the demonstrated and promising capabilities of MAN-IN-THE-SEA concepts and the recognized need for expanded R&D efforts to extend man's ability to live and work under the sea, the U.S. Navy must establish its long range goals and objectives for the exploitation of these concepts. An analysis of the potential contributions of MAN-IN-THE-SEA capabilities to the accomplishment of naval missions is needed to provide guidelines for the structuring of a long range MAN-IN-THE-SEA program. The objectives of this research effort sponsored by the Office of Naval Research are:

1. To identify and establish how, where, when, and why MAN-IN-THE-SEA concepts contribute to the accomplishment of naval missions.

2. To identify the research and development required to implement systems for the accomplishment of these naval missions.

This research memorandum reports the results of the first phase of the research effort. This phase concentrated on the definition of possible and unique MAN-IN-THE-SEA missions within the total spectrum of naval undersea missions and operations. The MAN-IN-THE-SEA missions defined during this phase will be the basis for the continuing study of the naval applications of MAN-IN-THE-SEA concepts.

B. Study Approach

The tasks essential to the study approach that was adopted are outlined in Figure 1. The tasks were to: (1) identify navy mission areas, related functions and tasks, and the required mission-performance capabilities; (2) define the performance capabilities of MAN-IN-THE-SEA concepts; (3) define the performance capabilities of alternative concepts; and (4) analyze and compare MAN-IN-THE-SEA concepts versus the alternatives. The study approach was aimed at defining MAN-IN-THE-SEA missions based on a critical assessment of the capabilities of man when exposed to ambient ocean pressure.

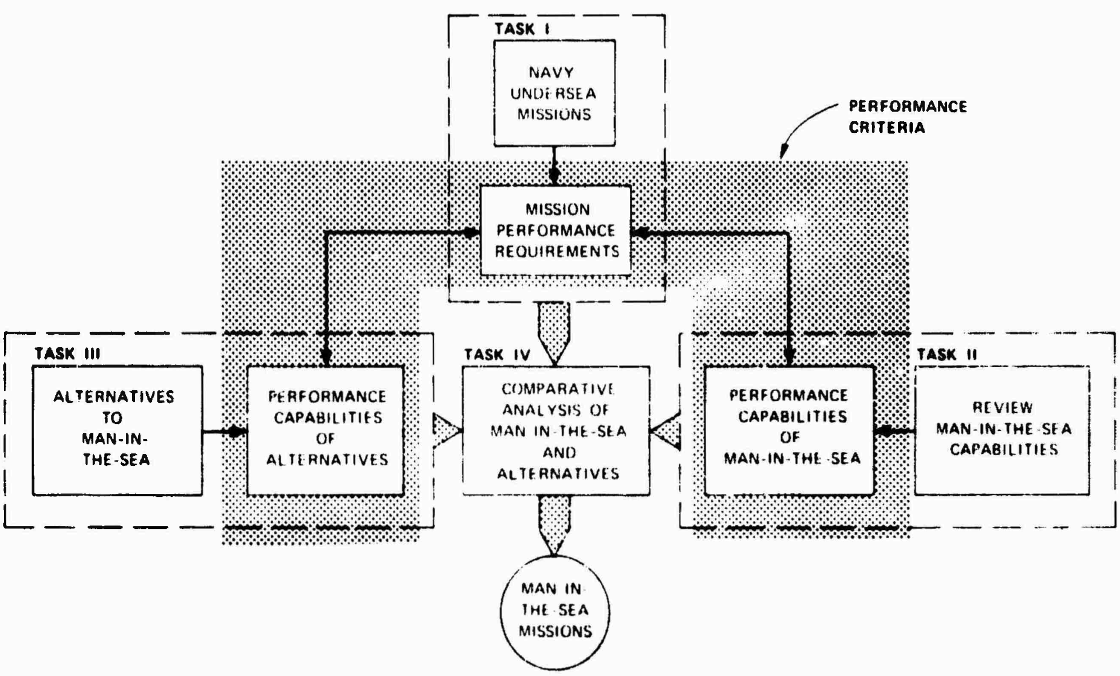

Figure 1 SUMMARY OF STUDY TASKS

The substance of the study approach lies in Task 4--that is, the comparative analysis of MAN-IN-THE-SEA concepts versus the alternatives. The major difficulty in establishing valid missions requiring the use of

MAN-IN-THE-SEA concepts is that there may be other means that could achieve the same missions. These alternatives might be tethered remote-controlled vehicles equipped with acoustic and visual sensors and manipulators or manned manipulator-equipped free swimming vehicles. The major advantage of these alternatives is that man is not directly exposed to the extremely hostile ambient underwater environment. The objectives of the first phase study were to identify those underwater tasks that require the capabilities of a man working in direct contact with his environment and relate those tasks to Navy underseas missions. In essence, the study sought answers to the following interrelated questions:

- What unique capabilities for accomplishing specific underwater tasks does an unshielded man have?
- Which Navy undersea missions have essential tasks requiring those unique capabilities?

The spectrum of Navy undersea missions and associated functions and tasks are identified in Section III. The performance criteria and definition of mission requirements (Section IV) and a compendium and description of alternative systems, including MAN-IN-THE-SEA systems (Section V), led to the comparative analysis of alternatives that provides the statement of MAN-IN-THE-SEA missions (Section VI). Reviews of the fundamentals and the performance capabilities of MAN-IN-THE-SEA concepts are provided in Appendixes A and B. A review of underwater mechanical manipulator capability is presented in Appendix C. Supporting data for naval undersea missions are presented in a classified addendum to this research memorandum.

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II SUMMARY

A. General

The naval undersea missions and operations requiring man's exposure to the ambient ocean environment defined in this study will serve as an input to a continuing study of the naval applications of MAN-IN-THE-SEA concepts for the 1975-1985 time frame.

A spectrum of naval undersea missions and operations was identified through a comprehensive review of total naval requirements in support of current and future national objectives. This type of review is considered to be a basic prerequisite for all naval supported, mission-oriented studies. The method used to identify naval undersea missions and operations was selected because it could provide requirement definitions that are related to, and supported by, current naval research planning procedures. As a result of this approach, a more complete and systematic overview of naval undersea operational requirements was achieved than was previously available.

The procedure used for identifying MAN-IN-THE-SEA missions and operations within the spectrum of naval undersea missions and operations was to compare the underwater performance capabilities of the unshielded man with the capabilities needed in those undersea systems that do not require man's exposure to the ambient ocean environment. Thus, the MAN-IN-THE-SEA mission definition study reported here <u>is unique in that the need for MAN-IN-THE-SEA concepts to accomplish particular naval missions and operations was not an initial study assumption</u>.

B. Study Results

The criteria used in defining the functional performance requirements related to the undersea naval missions and operations and the functional performance capabilities of alternative undersea systems were:

- Depth capability
- Time capability
- Mobility capability
- Load-carrying capability

- Maneuverability
- Manipulative capability
- Sensory capability
- Cognitive skills
- Hardness
- Covertness

The comparative analysis of the functional capabilities of MAN-IN-THE-SEA concepts versus the alternatives based on the foregoing criteria indicated that the unshielded man is unique only in the following sense:

1. He offers a singificant advantage in maneuverability because of his compactness, agility, and physical flexibility.

2. He offers a significant advantage in manipulative capability for tasks that require a high degree of finger dexterity.

3. He offers extended sensory capability because of his tactile senses. These senses enhance man's manipulative capability, especially in extremely turbid water.

4. He offers some degree of covertness in certain operational environments.

Tables 1 through 3 summarize the significant results of the present study and indicate:

1. Naval undersea missions and operations that could capitalize on the unique functional capabilities of the unshielded man.

2. Naval undersea missions and operations where both MAN-IN-THE-SEA and alternative systems would perform equally well.

3. Naval undersea missions and operations where alternative systems would provide a fundamental performance advantage.

Table 1 identifies MAN-IN-THE-SEA missions if system survivability during a mission emphasizes the use of covert operations. Table 2 provides similar information for the case where the use of hardened systems is emphasized. Table 3, which is an extension of Table 2, considers the possibility of designing undersea facilities to minimize constraints imposed by the limitations of mechanical manipulator equipped vehicle systems.

Table 1

DEFINITION OF MAN-IN-THE-SEA MISSIONS -- CONDITION I

CONDITION I:
MAN-IN-THE-SEA MISSIONS IF SYSTEM SURVIVABILITY DURING A MISSION EMPHASIZES THE USE OF COVERT OPERATIONS.

UNDERSEA FUNCTIONAL OPERATIONS	MAN-IN-THE-SEA CONCEPTS: FREE SWIMMING MAN	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: DIRECT SURFACE TETHER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: INDIRECT SURFACE TETHER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: HABITAT TETHER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: VEHICLE TETHER	ALTERNATIVES TO MAN-IN-THE-SEA CONCEPTS: MANNED FREE VEHICLE	ALTERNATIVES TO MAN-IN-THE-SEA CONCEPTS: TETHERED VEHICLE: MANNED TETHERED VEHICLE	ALTERNATIVES TO MAN-IN-THE-SEA CONCEPTS: TETHERED VEHICLE: UNMANNED TETHERED VEHICLE	ALTERNATIVES TO MAN-IN-THE-SEA CONCEPTS: FIXED BOTTOM STATION
SURVEILLANCE	X								X
● LANDING BEACH AREA	X								
● ENEMY HARBOR	X								
● U.S. HARBOR PROTECTION						X			X
● INSHORE USW	X								
● USW ALL RANGES & DEPTH						X			X
RECONNAISSANCE	X								
● BEACH AREA	X								
● ENEMY HARBOR	X								
● MINING ENVIRONMENT	X								
MINING	X	X	X	X	X	X			
● MINE HUNTING & COUNTERMEASURE	X								
● MINE PLANTS						X			
● DISARM MINE	X	X	X	X	X				
● INTERROGATE MINE FIELDS	X								
NAVIGATION SURVEYS						X			
RECOVERY	X	X	X	X	X	X	X	X	
● SMALL OBJECT						X	X	X	
TORPEDOES						X	X	X	
NUCLEAR WEAPON						X	X	X	
SPACE HARDWARE						X	X	X	
● LARGE OBJECT	X	X	X	X	X	X	X		
FACILITY INSTALLATIONS	X	X	X	X	X	X	X		
● SONAR ARRAY (ALIGN & REPAIR)	X	X	X	X	X	X	X		
● BOTTOM MOUNTED ULM	X	X	X	X	X	X	X		
● NAVIGATION MARKERS						X	X		
● CABLE LAYING & INSPECTION						X	X		
● GENERAL CONSTRUCTION	X	X	X	X	X	X	X		
● FOUNDATION & BOTTOM						X	X		
● TUNNELLING						X	X		
● DAM BUILDING						X	X		
● WELL DRILLING						X	X		
SALVAGE	X	X	X	X	X	X	X		
● SHIP	X	X	X	X	X	X	X		
● AIRCRAFT	X	X	X	X	X	X	X		
REPAIRS	X	X	X	X	X	X	X		
● IN PORT (WET DOCK)	X	X	X	X	X	X	X		
● UNDERWAY	X	X	X	X	X	X	X		
SUPPORT	X	X	X	X	X	X	X	X	X
● OCEANOGRAPHIC DATA						X	X	X	X
● SUB RESCUE PERSONNEL	X	X	X	X	X				
● UNDERWATER LOGISTICS	X			X	X				
HABITAT DEVELOPMENT	X	X	X	X	X	X	X		X

Table 2

DEFINITION OF MAN-IN-THE-SEA MISSIONS -- CONDITION II

CONDITION II:

MAN-IN-THE-SEA MISSIONS IF SYSTEM SURVIVABILITY DURING A MISSION EMPHASIZES THE USE OF HARDENED SYSTEMS.

UNDERSEA FUNCTIONAL OPERATIONS	MAN-IN-THE-SEA CONCEPTS: FREE SWIMMING MAN	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: DIRECT SURFACE TETHER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: INDIRECT SURFACE TETHER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: HABITAT TETHER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: VEHICLE TETHER	ALTERNATIVES TO MAN-IN-THE-SEA CONCEPTS: MANNED FREE VEHICLE	ALTERNATIVES TO MAN-IN-THE-SEA CONCEPTS: TETHERED VEHICLE: MANNED TETHERED VEHICLE	ALTERNATIVES TO MAN-IN-THE-SEA CONCEPTS: TETHERED VEHICLE: UNMANNED TETHERED VEHICLE	ALTERNATIVES TO MAN-IN-THE-SEA CONCEPTS: FIXED BOTTOM STATION
SURVEILLANCE						■			■
• LANDING BEACH AREA						■			■
• ENEMY HARBOR						■			■
• U.S. HARBOR PROTECTION						■			■
• INSHORE USW						■			■
• USW ALL RANGES & DEPTH						■			■
RECONNAISSANCE						■			
• BEACH AREA						■			
• ENEMY HARBOR						■			
• MINING ENVIRONMENT						■			
MINING	■	■	■	■	■	■			
• MINE HUNTING & COUNTERMEASURE						■			
• MINE PLANTS						■			
• DISARM MINE	■	■	■	■	■				
• INTERROGATE MINE FIELDS						■			
NAVIGATION SURVEYS						■			
RECOVERY	■	■	■	■	■	■	■	■	
• SMALL OBJECTS						■	■	■	
TORPEDOES						■	■	■	
NUCLEAR WEAPON						■	■	■	
SPACE HARDWARE						■	■	■	
• LARGE OBJECT	■	■	■	■	■	■	■		
FACILITY INSTALLATIONS	■	■	■	■	■	■	■		
• SONAR ARRAY (ALIGN & REPAIR)	■	■	■	■	■	■	■		
• BOTTOM MOUNTED ULM	■	■	■	■	■	■	■		
• NAVIGATION MARKERS						■	■		
• CABLE LAYING & INSPECTION						■	■		
• GENERAL CONSTRUCTION	■	■	■	■	■	■	■		
• FOUNDATION & BOTTOM						■	■		
• TUNNELLING						■	■		
• DAM BUILDING						■	■		
• WELL DRILLING						■	■		
SALVAGE	■	■	■	■	■	■	■		
• SHIP	■	■	■	■	■	■	■		
• AIRCRAFT	■	■	■	■	■	■	■		
REPAIRS	■	■	■	■	■	■	■		
• IN PORT (WET DOCK)	■	■	■	■	■	■	■		
• UNDERWAY	■	■	■	■	■	■	■		
SUPPORT	■	■	■	■	■	■	■	■	■
• OCEANOGRAPHIC DATA						■	■	■	■
• SUB RESCUE - PERSONNEL	■	■	■	■	■				
• UNDERWATER LOGISTICS	■			■	■				
HABITAT DEVELOPMENT	■	■	■	■	■	■	■		■

Table 3

DEFINITION OF MAN-IN-THE-SEA MISSIONS -- CONDITION III

CONDITION III.

AN EXTENSION OF TABLE 2 WHICH CONSIDERS THE POSSIBILITY OF DESIGNING UNDERSEA FACILITIES TO MINIMIZE CONSTRAINTS DUE TO THE LIMITATIONS OF MECHANICAL MANIPULATOR EQUIPPED VEHICLE SYSTEMS.

UNDERSEA FUNCTIONAL OPERATIONS

			SURVEILLANCE	• LANDING BEACH AREA	• ENEMY HARBOR	• U.S. HARBOR PROTECTION	• INSHORE USW	• USW ALL RANGES & DEPTH	RECONNAISSANCE	• BEACH AREA	• ENEMY HARBOR	• MINING ENVIRONMENT	MINING	• MINE HUNTING & COUNTERMEASURE	• MINE PLANTS	• DISARM MINE	• INTERROGATE MINE FIELDS	NAVIGATION SURVEYS	RECOVERY	• SMALL OBJECT	TORPEDOES	NUCLEAR WEAPON	SPACE HARDWARE	• LARGE OBJECT	FACILITY INSTALLATIONS	• SONAR ARRAY (ALIGN & REPAIR)	• BOTTOM MOUNTED ULM	• NAVIGATION MARKERS	• CABLE LAYING & INSPECTION	• GENERAL CONSTRUCTION	• FOUNDATION & BOTTOM	• TUNNELLING	• DAM BUILDING	• WELL DRILLING	SALVAGE	• SHIP	• AIRCRAFT	REPAIRS	• IN PORT (WET DOCK)	• UNDERWAY	SUPPORT	• OCEANOGRAPHIC DATA	• SUB RESCUE - PERSONNEL	• UNDERWATER LOGISTICS	HABITAT DEVELOPMENT
MAN-IN-THE-SEA CONCEPTS	FREE SWIMMING MAN												■			■			■					■											■	■	■	■	■	■	■		■		
	TETHERED MAN	DIRECT SURFACE TETHER											■			■			■					■											■	■	■	■	■	■	■		■		
		INDIRECT SURFACE TETHER											■			■			■					■											■	■	■	■	■	■	■		■		
		HABITAT TETHER											■			■			■					■											■	■	■	■	■	■	■		■		
		VEHICLE TETHER											■			■			■					■											■	■	■	■	■	■	■		■		
ALTERNATIVES TO MAN-IN-THE-SEA CONCEPTS	MANNED FREE VEHICLE			■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■
	TETHERED VEHICLE	MANNED TETHERED VEHICLE																	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■
		UNMANNED TETHERED VEHICLE																	■	■	■	■	■																		■	■			
	FIXED BOTTOM STATION		■	■	■	■	■	■																																	■	■			■

C. Emphasis of Continuing Study Effort

It is apparent that on a functional performance basis, MAN-IN-THE-SEA concepts and their alternatives are overlapping approaches for accomplishing a majority of the defined naval missions and operations, see Figure 2. The next study phase of naval applications of MAN-IN-THE-SEA concepts must place more emphasis on the capabilities of the alternatives. Furthermore, because of the overlapping nature of the undersea system concepts in performing the same functions, cost comparisons must be the basis for final selection of the means of accomplishing the defined naval undersea operations.

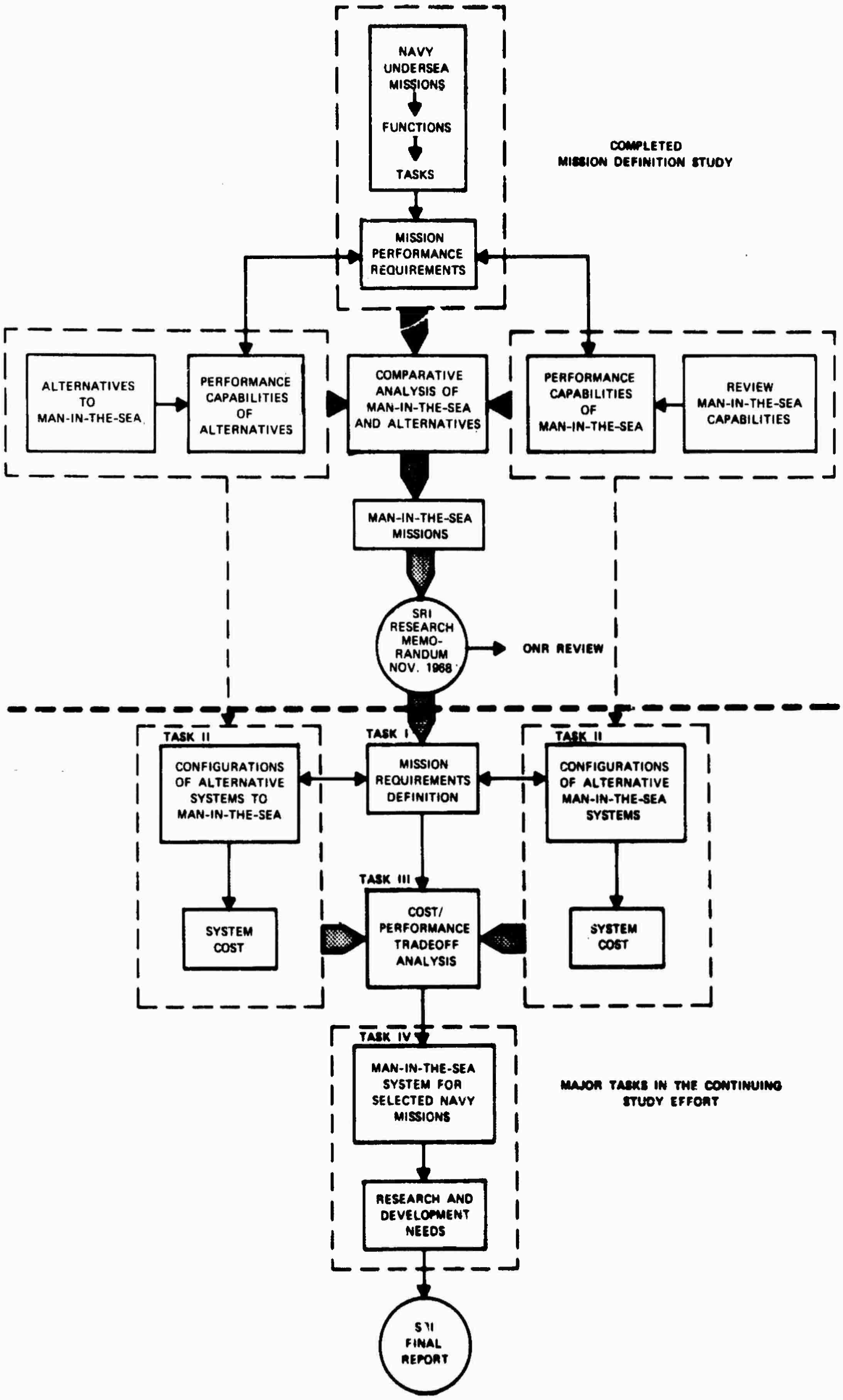

Figure 2 WORK FLOW DIAGRAM OF THE CONTINUING STUDY OF NAVAL APPLICATIONS OF MAN-IN-THE-SEA CONCEPTS

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III NAVAL UNDERSEA MISSIONS, OPERATIONS, FUNCTIONS, AND TASKS

A. General

This section describes the review of Naval Undersea Operational Requirements that was undertaken during the present study. The spectrum of naval undersea missions and operations was identified through a comprehensive review of total naval military requirements in support of current and future national objectives. This type of review is considered to be a basic prerequisite for all naval supported, mission-oriented studies. The method used to identify the naval underseas missions and operations was oriented to provide requirement definitions that are related to, and supported by, current Navy research planning procedures. The use of this approach resulted in a more complete and systematic overview of naval undersea operational requirements than was previously available.

Detailed undersea tasks associated with the spectrum of undersea missions and operations were defined as a result of a functional and task analysis for selected missions. These functions and tasks were the basis for the comparative analysis of MAN-IN-THE-SEA concepts versus the alternatives. This analysis determined the naval underseas missions and operations to which MAN-IN-THE-SEA concepts can directly contribute.

B. Naval Undersea Missions and Operations

1. Method of Definition

The method used to define naval undersea missions and operations is outlined in Figure 3. First, a thorough review was made of current naval warfare operations and applications as described in the NWPs and NWIPs. This review was accomplished, using the NWPs and NWIPs listed in Table 4. We used only those documents from the official list of tactical publications that in our judgment influence undersea operational requirements.

The planning objectives derived to that point then were reviewed, together with the General Operational Requirements (GOR), Specific Operational Requirements (SOR), Tentative Specific Operational Requirements

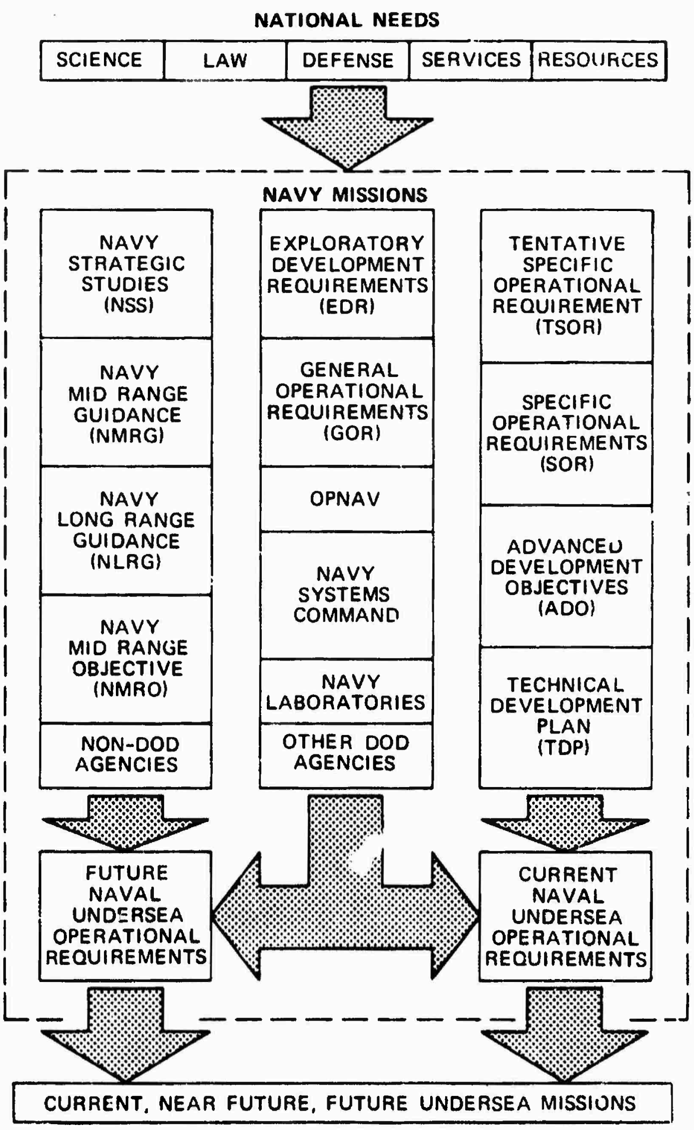

Figure 3 SUMMARY OF APPROACH TO THE IDENTIFICATION OF NAVY UNDERSEA MISSIONS

Table 4

TACTICAL PUBLICATIONS STATUS REPORTS

Short Title	Long Title	Classi-fication	Last Change
NWP 11-A	Naval Operational Planning	C	2 12 66
NWP 22-A	Doctrine for Amphib Operations	U	Orig. 7 62
NWIP 22-1B	The Amphibious Task Force Plan	U	Orig. 6 65
NWIP 22-4A	Underwater Demo Teams in Amphib Ops	C	Orig. 11 65
NWIP 23-1B	Submarine Primary Missions	C	Orig. 7 65
NWIP 23-2B	Submarine Support Operations	C	1 12 66
NWIP 23-9A	Submarine Evasion Manual	C	Orig. 12 62
NWP 24-B	ASW Operations	C	2 11 66
NWIP 24-1A	Antisubmarine Classification Manual	C	2 6 66
NWP 26-A	Mining Ops	C	1/2 1 66
NWIP 26-1	Minefield Planning	C	3 11 61
NWP 27-A	Mine Countermeasures Ops	C	Orig. 1 63
NWIP 27-1A	Supp to Mine Countermeasures Ops	S	1/1 5 65
NWIP 27-2	Minehunting Procedures	C	Orig. 7 64
NWP 28-A	Nuclear Warfare Operations	S	Orig. 10 66
NWIP 29-1	Seal Teams in Naval Special Warfare	S	Orig. 12 62
NWP 37-A	National SAR Manual	U	3 10 63
USN ADD 37-A	Sub Disaster SAR Ops	U	3 9 66
SUPP 37-A	Wartime Search and Rescue SAR Proc.	C	Orig. 8 65
NWP 38-B	Replenishment at Sea	U	1/1 12 65
NWP 39-A	Base Defense	U	1 4 66
NWP 40-A	Harbor Defense	C	Orig. 1 61

(TSOR), Advanced Development Objectives (ADO), and Technical Development Plans (TDP). A list of the GORs is given in Table 5.

The GORs broadly define the users' needs and directly reflect naval missions and operations. Following down the documentation chain of requirements for a development effort are the TSOR, a preliminary stated requirement; the SOR, a stated need; and the ADO, which indicates the direction of experimental development prior to an assumed military usefulness, which sometimes precedes the SOR.

The SOR, TSOR, and ADO are organized under the particular GORs listed here. They are indicated on the matrix prepared during this study (Table 6), when they directly or indirectly indicate a particular underwater functional requirement corresponding to the established list. The number or numbers assigned in each square correspond to a particular referenced document in the Reference Requirement List,* which states requirements and provides the details supporting those requirements. These documents, together with the NWPs and the NWIPs, form the basis of current operational requirements officially stated from CNO.

Concurrent with the review of the above naval documents, discussions were held with some potential users in the Navy Department concerning MAN-IN-THE-SEA capabilities and developments; these discussions uncovered other current and possible future potential undersea operations that were not described in the listed documents. These previously cited documents, together with the discussions, provided most all of the Navy's stated or contemplated requirements for underwater operations currently envisioned for the near future.

If the time scale for future operations is projected into the mid-1970s and early 1980s, however, the current stated naval undersea operational requirements are not complete and it becomes necessary to determine plausible naval undersea operations and the attendant technological requirements from other sources.

Future undersea naval requirements that are likely to evolve are those related to future operations as indicated in the Naval Strategic Studies, Mid-Range and Long-Range Guidance, Mid-Range Objectives, and Naval Support Plan. The requirements stated in these studies are much broader than, for example, the specific requirements as stated in the SOR. These long range studies (see Figure 3) helped to provide

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* The Reference Requirements List is presented in the classified addendum to this report.

Table 5

GENERAL OPERATIONAL REQUIREMENTS

10 Strike Warfare	20 Antisubmarine Warfare	30 Command Support	40 Operational Support
11 Airborne Attack	21 Airborne ASW	31 Command Control	41 Logistics
12 Surface Attack	22 Surface ASW	32 Naval Communications	42 Vacant
13 Submarine Attack	23 Submarine Surveillance	33 Electronic Warfare	43 Personnel
14 Amphibious Assault	24 Undersea Surveillance	34 Navigation	44 Astronautic Support
15 Strategic Deterrence	25 Mining	35 Ocean Surveillance	45 Aviation Support
16 Airborne Antiair	26 Mine Countermeasures	36 Reconnaissance and Intelligence	46 Ship Support
17 Surface Antiair	27 ASW Ancillary Support	37 Environmental Systems	47 Ordnance Support
18 Vacant		38 Special Warfare	48 NBC Defense

overall documentation for the development of naval underwater operational requirements of the future.

In conjunction with the foregoing sources, the project team sought information on possible future requirements concepts from laboratory personnel working in the R&D phases of naval weapons systems that are generated elsewhere within the Navy or DoD or by their respective contractors. Recent studies by Nortronics[1] and Op-03[2] have provided some of the projected requirements data for this study. One of these studies reported the results of contacting 21 DoD agencies, laboratories, and oceanographic institutes and distilling their ideas for future underwater operations into 9 functional operations.

2. Mission Requirements Matrix

Table 6 is a matrix representing results of the completed mission and operational requirements review. The naval mission requirements in the various documents were interpreted and organized under 10 broad, general underwater mission requirements stated in terms of functional operations. They are: surveillance, reconnaissance, mining, navigation, recovery, facilities installation, salvage, repairs, support, and habitat development.

The list of planning documents and related underwater functional operations in the matrix provides an immediate cross reference, showing which planning documents generate and provide specific requirements and the particular underwater functional operation these planning documents are concerned with.

The NWPs and NWIPs are broad Naval warfare planning documents; therefore, checks only have been used for cross referencing. A check is used to show that a particular planning document indicates either one or several underwater functional requirements or infers that these underwater operations will be carried out. The planning objectives, however, have been assessed differently in relating them to the broad underwater functional requirements. Under the planning objectives and organization are the several GORs, TSORs, and so forth. They have been reviewed and specific detailed requirements -- as stated in the documents -- are referenced with the assigned reference number indicated on the particular requirement. The number or numbers assigned in each square correspond to a particular referenced planning document in the Referenced Requirement List. These documents and the previously cited planning documents, the NWPs and the NWIPs,

Table 6

MISSION AND FUNCTIONAL OPERATIONAL MATRIX

PLANNING DOCUMENTS					PLANNING OBJECTIVES: STRIKE WARFARE								ANTISUBMARINE WARFARE							COMMAND SUPPORT								OPERATIONAL SUPPORT								UNDERSEA FUNCTIONAL OPERATIONS
NSS Naval Strategic Studies	NMRG Naval Mid-Range Guidance	NMLG Naval Long-Range Guidance	MRO Naval Mid-Range Objectives	NSP Naval Support Plan	11 Airborne Attack	12 Surface Attack	13 Submarine Attack	14 Amphibious Assault	15 Strategic Deterrence	16 Airborne Anti Air	17 Surface Anti Air	18 Vacant	21 Airborne ASW	22 Surface ASW	23 Submarine Surveillance	24 Undersea Surveillance	25 Mining	26 Mine Countermeasures	27 ASW Ancillary Support	31 Command Control	32 Naval Communications	33 Electronic Warfare	34 Navigation	35 Ocean Surveillance	36 Reconnaissance and Inte	37 Environmental Systems	38 Special Warfare	41 Logistics	42 Vacant	43 Personnel	44 Astronautic Support	45 Aviation Support	46 Ship Support	47 Ordnance Support	48 NBC Defense	
																			13								15	2		1			*			SURVEILLANCE ● Landing Beach Area ● Enemy Harbor ● U.S. Harbor Protection ● Inshore USW ● USW All Ranges and Depths
																			13								15			1			*			RECONNAISSANCE ● Beach Area ● Enemy Harbor ● Mining Environment
																			13											1			3,4 8,9			MINING ● Mine Hunting and Countermeasures ● Mine Plants ● Disarm Mine ● Interrogate Mine Fields
																							14					2					3,4			NAVIGATION SURVEYS
																												2		1			† 16 6			RECOVERY ● Small Objects ● Torpedoes ● Nuclear Weapons ● Space Hardware ● Large Objects
									11																			2		1			3,4 18	17		FACILITY INSTALLATIONS ● Sonar Array ● Bottom Mounted ULM ● Navigation Markers ● Cable Laying and Inspection ● General Construction ● Foundation and Bottom ● Tunnels ● Dams ● Wells
																												2		1			3,4 5			SALVAGE ● Ships ● Aircraft
																												1					3			REPAIRS ● In Port ● Underway
			20																									2					3,4 5,18			SUPPORT ● Oceanographic ● Sub Rescue Personnel ● Undersea Logistics
																												2		1			3,4 18			HABITAT DEVELOPMENT

* 3, 4, 8, 9, 13

† 3, 4, 10, 13, 18

Table 6 (concluded)

UNDERSEA FUNCTIONAL OPERATIONS	OPERATIONAL DOCTRINE																	
	NWP 11A Naval Operational Planning	NWP 22A Doctrine for Amphibious Operations	NWIP 22-1B The Amphibious Task Fr Pl	NWIP 22-4A UDT in Amphibious Operations	NWIP 22-5A The Naval Beach Group	NWIP 23-2B Submarine Support Operations	NWP 24B ASW Operations	NWIP 24-1A ASW Classification Manual	NWP 25 Mobile Logistic Support Operations	NWP 26A Mining Operations	NWIP 26-1 Minefield Planning	NWIP 27A Mine Countermeasures Operations	NWIP 27-1A Support to Mine Countermeasures Operations	NWIP 27-A Minehunting Procedures	NWIP 29-1 Seal Teams in Sp. War	USN Add 27A Submarine Disaster SAR Operations	NWP 36B Replenishment at Sea	NWP 40A Harbor Defense
SURVEILLANCE																		
• Landing Beach Area		✓		✓	✓	✓				✓	✓	✓	✓		✓			
• Enemy Harbor		✓		✓	✓	✓				✓	✓				✓			
• U.S. Harbor Protection										✓	✓	✓	✓					✓
• Inshore USW		✓		✓			✓			✓	✓				✓			✓
• USW All Ranges and Depths							✓											
RECONNAISSANCE															✓			
• Beach Area		✓		✓	✓	✓				✓	✓	✓	✓		✓			
• Enemy Harbor		✓		✓	✓	✓				✓	✓	✓	✓		✓			
• Mining Environment		✓		✓	✓	✓				✓	✓	✓	✓					
MINING										✓								
• Mine Hunting and Countermeasures		✓		✓								✓	✓	✓				✓
• Mine Plants		✓				✓				✓	✓							✓
• Disarm Mine				✓							✓	✓						✓
• Interrogate Mine Fields											✓	✓	✓					✓
NAVIGATION SURVEYS																		
RECOVERY																		
• Small Objects																		
• Torpedoes																		
• Nuclear Weapons				✓														
• Space Hardware																		
• Large Objects																		
FACILITY INSTALLATIONS																		
• Sonar Array							✓											
• Bottom Mounted ULM																		
• Navigation Markers																		
• Cable Laying and Inspection							✓											
• General Construction																		
• Foundation and Bottom																		
• Tunnels																		
• Dams																		
• Wells																		
SALVAGE																		
• Ships																		
• Aircraft																		
REPAIRS																		
• In Port																		
• Underway																		
SUPPORT																		
• Oceanographic		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
• Sub Rescue Personnel																✓		
• Undersea Logistics		✓	✓	✓	✓		✓		✓								✓	
HABITAT DEVELOPMENT																		

* 3, 4, 8, 9, 13
† 3, 4, 10, 13, 18

form the basis of current operational requirements officially stated by the Chief of Naval Operations.

C. Undersea Tasks Analysis

1. Analysis Method Used

Undersea tasks associated with the spectrum of navy undersea missions or functional operations were derived through the following method. First, two functional operations listed in Table 6 were selected as focal points for the task analysis. The functional operations selected were salvage or recovery operations and the undersea logistic transfer aspects of the support operation. The first, salvage or recovery, was selected because it is a real current navy requirement and will remain so in the near future. The second, the undersea logistic transfer aspects of the support operation, represents a projected requirement or a somewhat negligible current requirement. The two extremes were selected to focus the task analysis on uncovering a spectrum of undersea tasks on which to base the comparative analysis of alternatives. In addition to the task analysis conducted for the salvage and logistic transfer operations, the project team reviewed a number of documents generated in the past that identify undersea tasks. This review together with the results of the task analysis effort provided a compendium of current and projected undersea tasks.

2. Salvage Requirements and Tasks

a. Requirements. Much of the MAN-IN-THE-SEA future support for Naval requirements stems from the possible extension of operational depths of free swimmers/divers down to and beyond the continental shelf depths for possible future salvage requirements. The establishment of these future requirements appears to have been originated by the DSSRG report of 1 March 1964, which was concerned primarily with submarine rescue. Other salvage requirements are also established within GOR 46, Operational Support, and the related TSORs, SORs, and ADO, although these documents were all initiated after 1 March 1964. In particular, SOR 46-16, Object Location and Small Object Recovery, and SOR 46-17, Large Object Salvage System (LOSS) are concerned with recovery of large objects, which are defined as having a dead weight of 1000 tons or more. Included within the LOSS limits are submarines. Small objects are considered to be larger than a basketball and less than 10 tons.

P. 22 - Blank

With the advent of nuclear power and atomic warheads, the salvaging of submarines and their missile warheads becomes much more significant than ever before, with worldwide political overtones. From a realistic point of view, the loss of the military personnel and equipment and their "dollar" costs would appear to be subordinate to the primary need to salvage all equipment and weapons related to atomic energy. The worldwide alarm over the potential actuation of, or radiation from, any nuclear device in the ocean stems from the past record of the B-52 which crashed in Thule, Greenland, with an atomic weapon aboard, and a similar accident off Palomares, Spain. This type of salvage may not have an immediately obvious economic value other than the cost of producing the atomic weapon, but surely its intangible value is large when most of the world's governments are concerned when a U.S. military accident involves atomic weapons.

Salvage operations on a nuclear submarine could, and probably would be, carried out just to determine the cause of the sinking. This prospect is partly evidenced by the extensive search for any remaining structure to indicate why or how the Thresher failure occurred.

Other immediate and very possible salvage requirements would be concerned with any naval ship sunk, particularly in a harbor or shallow water. Furthermore, aircraft, space hardware, and maritime shipping have definite salvage requirements. The costs of shipbuilding and reoutfitting versus the salvage costs would necessarily be a prime consideration in decisions related to salvage of naval ships, commercial maritime cargo carriers, and harbor barges. This type of salvage would probably have distinct economic values that could be easily assessed.

Aircraft salvage and space hardware, being much smaller and lighter, could have a higher probability of salvage success, but their tangible value is less significant than the intangible values, such as learning how well the space hardware did or did not function or what caused the aircraft failure. It is in this area of aircraft salvage that a large part of the current Navy salvage participation occurs. Almost 50% of the salvage operations conducted by the Navy during 1966, 1967, and most of 1968 were for aircraft belonging either to the Navy, Marine Corps, or the Air Force. A partial listing of recent and current salvage operations under cognizance of the Naval Salvage Office is provided in Table 7. The operations listed are extracts from the more recent "hot sheets", which are filed chronologically in the Office of Supervisor of Salvage, NSSC.

Table 7

RECENT AND CURRENT SALVAGE OPERATIONS
UNDER THE COGNIZANCE OF THE NAVAL SALVAGE OFFICE

Salvage Object	Geographical Location	Depth, if Known	Date
F-4C	Gulf of Mexico		29 Mar 66
F-100	Coast of Florida		
Japan hulk	My Tho (RVN)*	x	25 May 66
F-8-E	Kaneohe Bay		2 Jun 66
USAF F-106	Lake Huron		15 Jun 66
MSO-493	San Juan	29 feet	27 Jun 66
USAF C-130	Cape Vorella	300-500 feet	6 Jul 66
SS Taestus (Italy)	Cape Hateras		11 Jul 66
50 ton barge	Harbor (RVN)		11 Jul 66
160 tons of ammo	Off a barge (RVN)		3 Aug 66
USAF F-84	Lake Michigan		18 Aug 66
USAF F-102	New Orleans		27 Sep 66
8-man helicopter	Gulf of Mexico		12 Oct 66
USAF F-105	Gulf of Mexico	60-100 feet	15 Oct 66
SS Golden State	Manila	deep water	22 Oct 66
MSB-54	Nha Be (RVN)		31 Oct 66
USAF EC-121	Nantucket	180 feet	12 Nov 66
F-8	San Diego		21 Nov 66
SS Daniel J. Morrell	Lake Huron	200 feet	Dec 66
LST-912	Chu Lai (RVN)		4 Jan 67
MSB-45	RVN*		21 Jan 67
Dredge	RVN	20 feet	1 Feb 67
HU-16 E	Gulf of Mexico		6 Mar 67
USMC F-8-D	Kaneohe Bay		28 Feb 67
USAF F-102	Keohi Pt.		21 Mar 67
USN A-6-A Intruder	Cape Hateras	40 feet	5 Apr 67
USAF C-141	Cam Ranh Bay (RVN)		13 Apr 67
Super Connie	Nantucket		25 Apr 67

* Combat Harbor Clearance.

b. <u>Salvage Tasks</u>. In the general salvage operations, there are basic, distinct salvage functions that must be performed. These functions are isolated and indicated in the diagram in Figure 4.

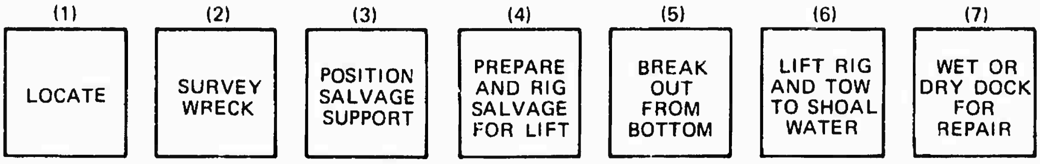


Figure 4 OVERALL SALVAGE FUNCTIONS

Seven subfunctional tasks for the salvage operation have been indicated in the figure: locate the wreck, survey the position of the salvage on the bottom, bring support equipment into the most optimum position for support, prepare and rig the salvage for lift, break out the salvage if and when embedded in soft bottoms, lift the salvage and tow to shallow water, and position salvage for either wet or dry dock repairs.

Each of these subfunctional tasks in turn is further broken down to provide a more detailed description of the requirements entailed in each function. These breakdowns are shown in Figures 5 through 7. As will be noted from the figures, not all subfunctions require a particular operation from below the surface--e.g., the subfunctions to locate salvage, position the salvage support systems, and position salvage for wet or dry dock repairs require no particular diver functional operation and are included only for completeness.

The initial search for the sunken object does not concern the diver directly. Because of his limited detection ranges relative to other search systems, he becomes involved in the operation only after the position of the object is precisely determined. The initial part of the total salvage operation is not outlined here. However, the Thresher search, for example, indicates that underwater vehicles and surface search by dragging hooks, magnetic and acoustic devices, underwater photography, and television cameras all will probably prevail. Other salvage subfunctions, like position salvage support systems, will probably require only a few buoy plants and no divers. Towing and placing salvage in port for dry dock repairs also will not require divers except for checking the integrity of towing rigs.

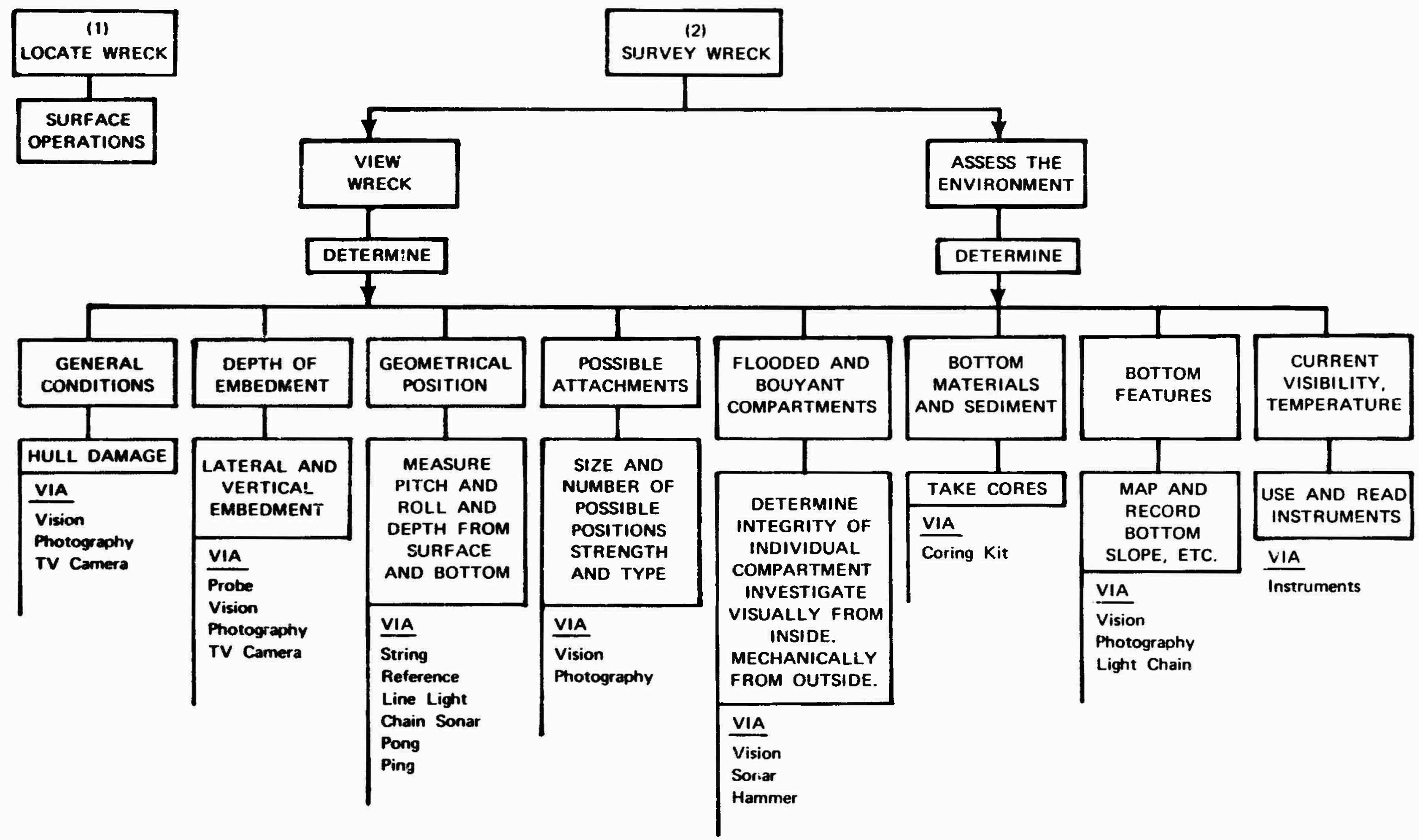


Figure 5 LOCATE AND SURVEY WRECK FUNCTIONS

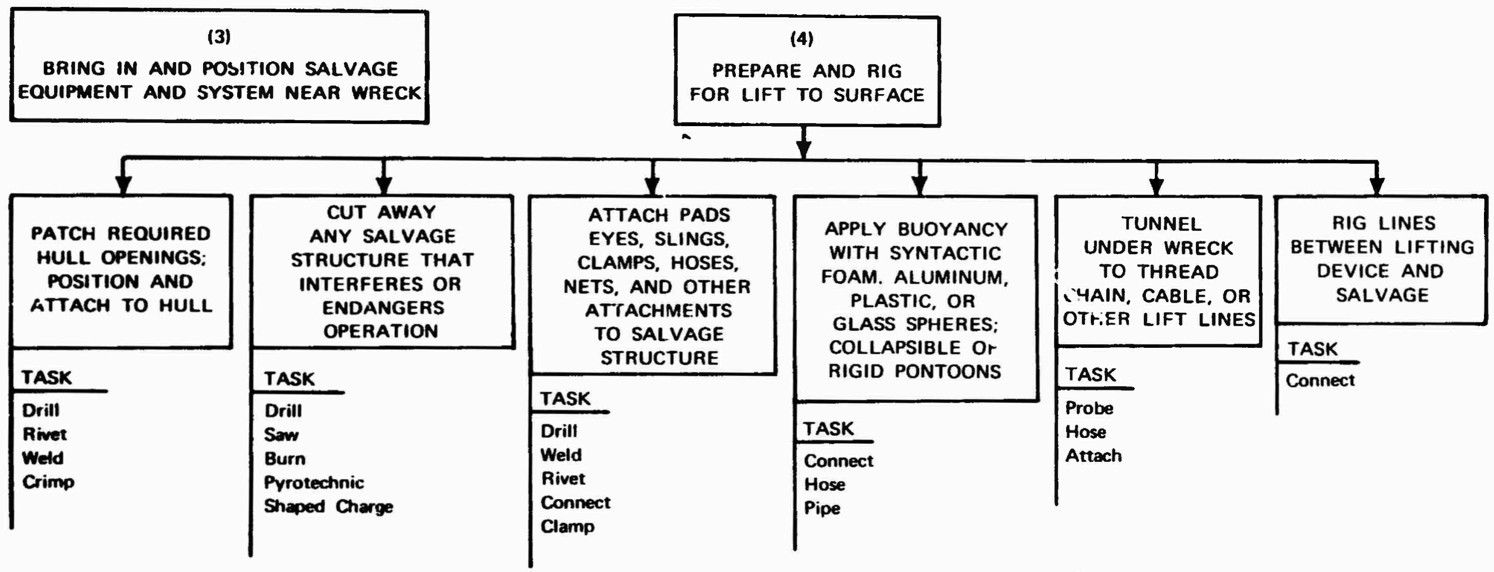


Figure 6 POSITION SALVAGE EQUIPMENT AND RIG FOR LIFT FUNCTIONS

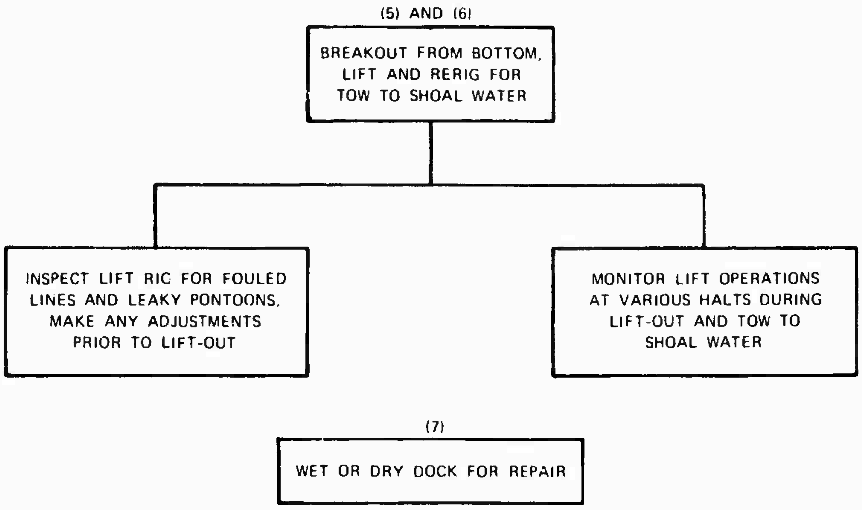


Figure 7 BREAKOUT FROM BOTTOM AND LIFT FUNCTIONS

The candidate tools to perform the particular tasks designated in the salvage subfunctions are shown in Table 8. This matrix of tasks will serve as an aid to understanding the required underwater manipulations in performing the various tasks to fulfill the salvage mission.

3. Undersea Logistic Transfer and Tasks

Task analysis for undersea logistic transfer is contained in the classified addendum to this research memorandum.

4. Task Spectrum

In addition to those tasks identified for the selected salvage and logistic transfer operations, a compendium of undersea tasks was put together through a review of various references[3-8]. The studies reviewed were conducted to identify current and projected design requirements for divers' tools and to apply the findings to the study of deep submergence vehicle and vehicle design requirements. The compendium of tasks resulted from a fairly exhaustive search and definition of current and foreseeable undersea tasks. While many studies provide breakdowns of undersea tasks, it became apparent very early in the review that the referenced studies represented the consensus on possible underwater tasks. For instance, oceanographic studies will indicate that instrument pickup, transportation, and placement are

Table 8

RELATIONSHIP OF SALVAGE TASKS AND UNDERSEA TOOL REQUIREMENTS

TASKS \ TOOLS	Saw-Powered	Saw-Hand	Saw-Zero Reaction	Shears	Open & Box Wrenches	Adjustable Wrench	Ratchet Wrenches	Power Wrench-Impact	Wrench-Zero Reaction	Screwdriver	Ratchet Screwdriver	Screwdriver-Zero Reaction	Hammer-Hand	Hammer-Magnetomotive	Drill-Powered	Drill-Hand	Drill-Zero Reaction	Punch-Magnetomotive	Punching Head	Riveter-Magnetic	Stud Gun & Fastener	Crimping Tool	Vacuum Tool	Electron Beam Gun	Arc/Oxygen	Oxygen/Hydrogen	Metal/Arc Torch	Coring Kit	Guide Pins	Coupling Fasteners	Slings & Rigging Gear	Clamps	Ice Tongs-Clam Grip	Jacks & Levers	Winches & Hoist	Nylon Line	Levels	Chisels & Caulking Tools	Levers	Manipulators	Brushes	Inflatable Bags	Foam Guns	Pyro-Technic Charge	TV Camera	Work Gloves & Pads	Knife	Illumination Kit	Tool Kit Container	Squalus Washer	Probe	Hardlines
Cutting																																																				
• Sawing	X	X	X																																											X		X	X			
• Shearing				X																																										X		X	X			
• Burning																											X																			X		X	X			
• Pyrotechnics																																												X		X		X	X			
Torqueing					X	X	X	X	X	X	X	X																																		X		X	X			
Hammering													X	X																																X		X	X			
Drilling															X	X	X																													X		X	X			
Punching																		X	X																											X		X	X			
Stud Driving																																																				
• Riveting																				X	X																									X		X	X			
• Fastening																				X	X																									X		X	X			
Sealing																																																				
• Crimping																						X																										X	X			
• Vacuumizing																							X																									X	X			
Welding																								X	X	X	X														X					X		X	X			
Coring															X	X	X											X																				X	X			
Calking/Coating													X																									X								X		X	X			
Guiding/Positioning																													X		X	X		X	X	X	X		X	X						X		X	X			X
Connect/Disconnecting					X	X	X	X	X	X	X	X	X							X	X			X	X	X			X	X	X	X	X		X	X			X					X		X	X	X	X			
De-Embedding																																																				
• Raising															X	X	X			X	X			X	X	X				X	X	X	X	X	X	X			X	X		X	X			X		X	X			
• Dislodging													X																		X			X				X	X	X		X		X		X	X	X	X	X	X	X
• Excavating																																														X					X	

Source: Reference 15.

the required set of underwater tasks. The vehicle manipulator studies specify torpedo pickup and transportation as a set of underwater tasks. It is obvious that both sets of tasks correspond to the same general set of undersea activities. By correlating the tasks described in each study, including those tasks described in the task analysis effort of this study (Section III), a list of generalized tasks were generated. This generalized task spectrum covers nearly all the current undersea tasks and the foreseeable future undersea tasks. For convenience, the generalized task spectrum is divided into four classes of activities. Class I is the general search or location task; Class II includes the observation, surveying, and measurement tasks; Class III includes the simple pickup, transport, and placement tasks; and, finally, Class IV represents the whole group of manipulative activities that include the attachment, detachment, application, and excavation tasks. These tasks are described briefly in the following paragraphs:

- Class I: Search

  The search task includes activities associated with the location of lost objects, wrecks, submarines, mines, bottom features, and so forth. The search/location task is conducted over a large area of the ocean bottom, with visual, acoustic, electromagnetic, magnetic, or electric sensors.

- Class II:

  - Observation

    The observation task entails the monitoring of activities through the use of visual, acoustic, electromagnetic magnet, or electric sensors. Examples of this task are harbor surveillance, submarine detection, and swimmer detection.

  - Survey

    The survey task includes such activities as the inspection of wrecks, recording via photography or sonar, and determination of general conditions of underseas structures.

  - Measure

    The measurement task includes such activities as the determination of bottom slope, bottom hardness, water temperature, and water turbidity; the majority of oceanographic data gathering activities might be classified as measurement tasks.

- Class III:

  - Pickup

    The pickup task entails activities associated with the recovery of small objects. Recovery of torpedoes, space re-entry bodies, bombs, and the like requiring only simple grappling action are simple pickup tasks.

  - Transport

    The transport task is simply the moving of an object from A to B point.

  - Place

    The placement task entails activities associated with the deployment of bottom moored mines, bottom navigation markers, or oceanographic instruments.

- Class IV:

  - Attachment

    The attachment task includes a whole range of activities from the mounting of patch on wrecks, to the mounting of lifting padeyes to recovery objects, to the hooking up of connectors, such as air hose or pipelines. The task can be broken down into the subtasks of drilling, bolting, riveting, hooking up, clamping, and so forth.

  - Detachment

    The detachment task includes the spectrum of activities from removal of sections of a salvage object through clearing of lines, to removal of marine growth from undersea objects. The task can be broken down into the subtasks of drilling, burning, hammering, chipping, scraping, and the like.

  - Apply

    The application task includes such activities as the placement of foam for the flotation of wrecks and the application of paint on undersea structures.

  - Excavate

    The excavation task includes such activities as trenching, tunneling, coring, and dredging. The generalized task spectrum is summarized in Table 9.

Table 9

THE GENERALIZED TASK SPECTRUM

Class	Task	Subtask
I	Search/Locate	
II	Observe	
	Survey	
	Measure	
III	Pickup	
	Transport	
	Place	
IV	Attach	• Drill • Bolt • Rivet • Connect/Hook Up • Clamp
	Detach	• Drill • Burn • Saw • Hammer • Chip • Scrape • Wipe
	Apply	• Hose • Paint
	Excavate	• Core • Dredge • Trench • Tunnel

5. Functional Operations and Task Relationship

Each Navy undersea functional operation defined in Table 6 has an associated set of tasks (Table 9). These functional operations and task relationships are given in Table 10. The Xs identify tasks associated with each subdivision of a major functional operation--e.g., small object or large object recovery within the overall functional operation heading of "Recovery." All tasks associated with an overall functional heading, such as "Recovery," "Facilities Installation," or "Salvage," are shown in the shaded row.

Table 10

IDENTIFICATION OF TASKS WITHIN THE NAVY UNDERSEA FUNCTIONAL OPERATIONS

UNDERSEA FUNCTIONAL OPERATIONS \ GENERALIZED TASK SPECTRUM	CLASS I: SEARCH/LOCATE	CLASS II: OBSERVE	CLASS II: SURVEY	CLASS II: MEASURE	CLASS III: PICKUP	CLASS III: TRANSPORT	CLASS III: PLACE	CLASS IV: ATTACH (DRILL, BOLT, RIVET, CONNECT/HOOKUP, CLAMP)	CLASS IV: DETACH (DRILL, BURN, SAW, HAMMER, CHIP, SCRAPE, WIPE)	CLASS IV: APPLY (FILL) (HOSE, PAINT)	CLASS IV: EXCAVATE (CORE, DREDGE, TRENCH, TUNNEL)	COMMENTS
SURVEILLANCE												
Landing Beach Area		X	X		X	X	X					
Enemy Harbor		X	X		X	X	X					
U.S. Harbor Protection		X	X		X	X	X					
Inshore USW		X	X		X	X	X					
USW All Ranges & Depths		X	X		X	X	X					
RECONNAISSANCE												
Beach Area	X		X	X	X	X	X					
Enemy Harbor	X		X	X	X	X	X					
Mining Environment	X		X	X	X	X	X					
MINING												
Mine Hunting and Countermeasures	X		X	X		X	X					
Mine Plants						X	X					
Disarm Mine								X	X			
Interrogate Mine Fields	X	X	X									
NAVIGATION SURVEYS												
RECOVERY												
Small Object	X		X		X	X						
• Torpedoes	X		X		X	X						
• Nuclear Weapons	X		X		X	X						
• Space Hardware	X		X		X	X						
Large Object	X		X	X	X	X	X	X	X	X	X	
FACILITY INSTALLATIONS												
Sonar Array (align & repair)			X	X	X	X	X	X	X	X		
Bottom Mounted ULM			X	X	X	X	X	X	X	X	X	
Navigation Markers			X	X	X	X	X					
Cable Laying & Inspection			X	X	X	X	X					
General Construction			X	X	X	X	X	X	X	X	X	
Foundation & Bottom										X	X	
Tunnelling										X	X	
Dam Building										X	X	
Well Drilling										X	X	
SALVAGE												See Sec. III-C-3
Ships	X	X	X	X	X	X	X	X	X	X	X	
Aircraft	X	X	X	X	X	X	X	X	X	X	X	
REPAIRS												
In Port (Wet Dock)								X	X	X		
Underway								X	X	X		
SUPPORT												
Oceanographic Data		X	X	X	X	X	X	X	X	X	X	See Ref. 4
Sub Rescue Personnel	X	X	X			X	X	X	X	X	X	
Underwater Logistics		X			X	X	X	X	X			See Sec. III-C-3
HABITAT DEVELOPMENT												

IV FUNCTIONAL PERFORMANCE REQUIREMENTS

A. Performance Criteria

Ten basic criteria were chosen for evaluating functional performance in this study. These criteria will be used here to provide a general statement of functional performance requirements--that is, a definition of capabilities required to perform the undersea functional operations defined in Table 6. These same criteria are used as the basis for defining the capabilities of MAN-IN-THE-SEA concepts and alternatives (Section V). Finally, the defined functional performance requirements and alternative capabilities stated in terms of these 10 basic functional performance criteria are used for the comparative analysis of alternatives (Section VI).

The 10 basic functional performance criteria are depth, time, mobility, load carrying, maneuverability, manipulation, sensing, cognition, hardness, and covertness. The first two--depth and time--were the primary performance criteria used in the past to assess and select alternative systems for mission performance. However, in the analysis conducted during this study, simple, depth-time statements of requirements and capabilities were not adequate, as will become clear in the comparative analysis described in Section VI. Each of the defined basic performance criteria and its major considerations are:

Depth

The depth criterion is concerned with (1) the mean depth requirement for projected functional operation, (2) the maximum depth capability of an alternative system, and (3) the excursion depth requirements of an operation and the excursion depth capability of alternative systems. Excursion depth means the depth range variation about the required mean operating depth and the depth range capability of alternative systems.

Time

The time criterion is concerned with (1) the time required to complete a projected functional operation and (2) the reaction time requirement and the reaction time capability of alternative systems. The reaction time is the time required to move from staging point to job site.

Mobility

The mobility criterion is concerned with (1) the speed of motion required to complete a projected functional operation and the speed capability of the alternative system and (2) the range coverage required to complete a projected functional operation and the range capability of the alternative systems. In some instances, speed-range criteria might be combined to form the single criterion of endurance requirement or capability. In addition to the speed criterion, which generally refers to horizontal motion, it is necessary to add the vertical rate of motion as a mobility criterion for the statement of requirements and capabilities.

Load Carrying

The load carrying criterion is concerned with (1) the size and weight of the object that must be transported to satisfy a projected functional operation and (2) the size and weight that alternative systems are capable of carrying.

Maneuverability

The maneuverability criterion is concerned with (1) the access limits associated with a projected functional operation and the ability of a system to reach tight spaces and (2) the degree of freedom available in each of the alternative systems.

Manipulation

The manipulation criterion is concerned with all motions and applied forces that are associated with hand, arm, and shoulder actions of man in accomplishing work. A representation division of manipulative criterion is the statement of degree of skill required to accomplish a given task. For the purposes of this study manipulative measures are divided into minimum, moderate, and complex skill levels.

Sensing

The sensing criterion is concerned with (1) the visual, acoustic, electromagnetic, and tactile senses required to accomplish funcional operations and (2) the capabilities of alternative systems for meeting these requirements.

Cognition

The cognition criterion refers specifically to (1) the cognitive skills required to make an on-site assessment of a given functional operation and (2) the on-site assessment capability of the alternative systems.

Hardness

The hardness criterion is concerned with (1) the resistance requirement to hazards, such as explosion (mechanical), nuclear radiation, temperature, and marine life, during the accomplishment of projected functional operations and (2) the resistance capability of alternative systems to hazards.

Covertness

The covertness criterion is concerned with (1) the required resistance to detection by visual, acoustic, magnetic, and electrical sensors during the accomplishment of a projected functional operation and (2) the ability of alternatives to avoid detection by the various sensors.

The 10 basic performance criterion are separated into four groups and summarized in Figure 8.

B. Performance Requirements Definition

The mission, functional operation, and generalized tasks relationship developed in Section II and presented in Tables 6 and 10 are the basis for the development of the functional performance requirements matrix shown in Table 11. The functional performance requirements shown in this table are subjective estimates of future requirements. They are qualitative statements that tend to set the boundaries for requirements rather than specific quantitative statements of those requirements. The latter can only be arrived at through a comprehensive mission and functional operations analysis. Such a comprehensive analysis of each functional operation was not deemed necessary in this study. Table 6, which identifies the sources of naval undersea functional operations, is incorporated in Table 11 for the sake of completeness.

In relating the functional operations to a particular subcategory of the functional performance requirements, some general interpretations have been made of the particular requirements of depth, travel time, duration of operation, speed, range, endurance, object size, and object weight. In all other descriptions of functional performance requirements, a check in the appropriate row and column of the Functional Operation and Functional Performance Requirement Matrix indicates only that the particular functional operation is supported by the indicated functional requirement. Such requirements as travel time and mission duration time are estimated to be in the order of hours or days. Speed and endurance

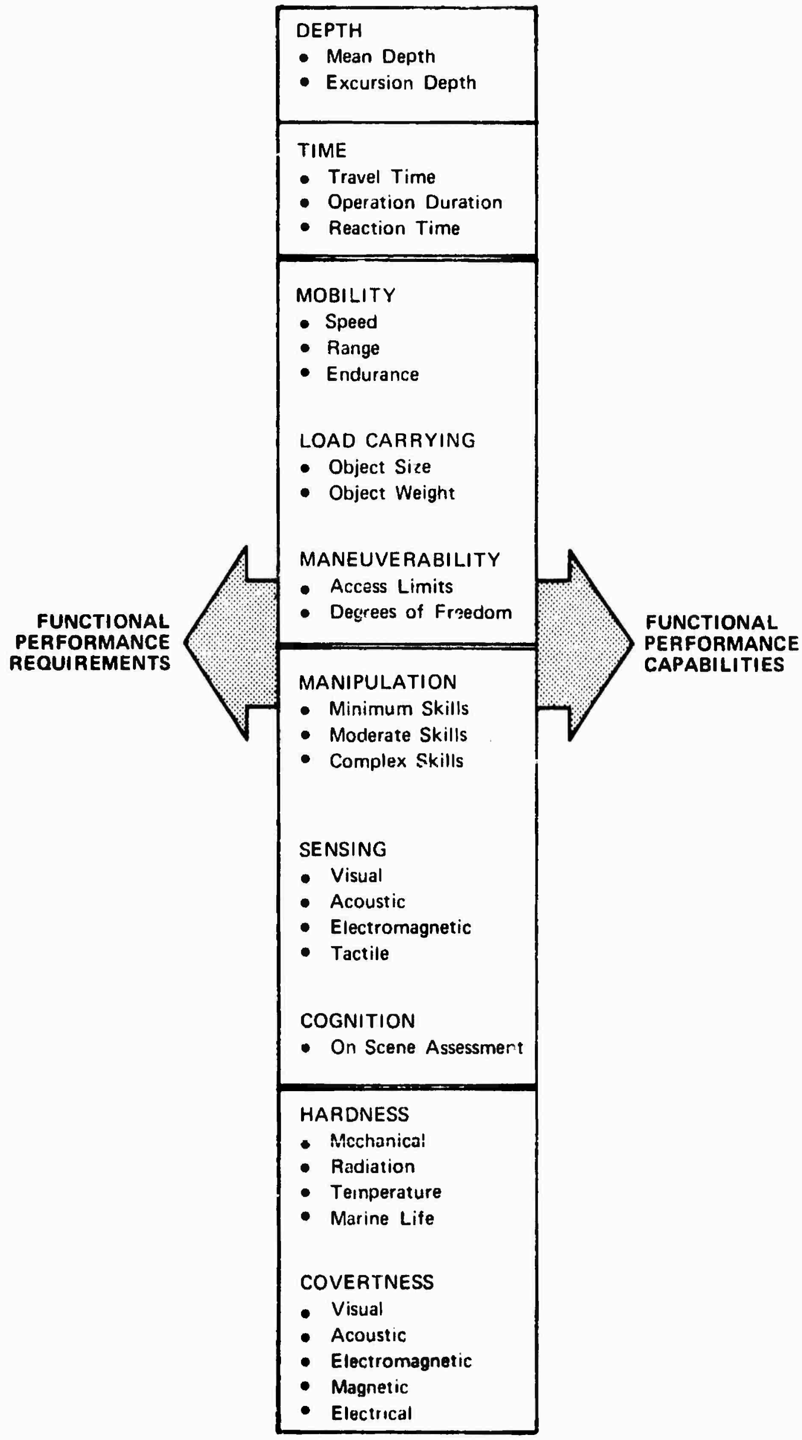


Figure 8 SUMMARY OF GOVERNING PERFORMANCE CRITERIA FOR THE STATEMENT OF FUNCTIONAL PERFORMANCE REQUIREMENTS AND CAPABILITIES

Table 11

MISSIONS, OPERATIONS, AND FUNCTIONAL REQUIREMENTS MATRIX

- H = hours
- D = days
- a = less than 100 miles
- b = very short, operation independent of range
- ℓ = large
- s = small
- W_W = world wide
- 1 = very important to success
- 2 = important to success
- 3 = not too important to success
- 4 = unimportant to success

	PLANNING OBJECTIVES																																			
	PLANNING DOCUMENTS					STRIKE WARFARE								ANTISUBMARINE WARFARE							COMMAND SUPPORT								OPERATIONAL SUPPORT							
UNDERSEA FUNCTIONAL OPERATIONS	NSS Naval Strategic Studies	NMRG Naval Mid-Range Guidance	NMLG Naval Long-Range Guidance	MRO Naval Mid-Range Objectives	NSP Naval Support Plan	11 Airborne Attack	12 Surface Attack	13 Submarine Attack	14 Amphibious Assault	15 Strategic Deterrence	16 Airborne Anti Air	17 Surface Anti Air	18 Vacant	21 Airborne ASW	22 Surface ASW	23 Submarine Surveillance	24 Undersea Surveillance	25 Mining	26 Mine Countermeasures	27 ASW Ancillary Support	31 Command Control	32 Naval Communications	33 Electronic Warfare	34 Navigation	35 Ocean Surveillance	36 Reconnaissance and Inte	37 Environmental Systems	38 Special Warfare	41 Logistics	42 Vacant	43 Personnel	44 Astronautic Support	45 Aviation Support	46 Ship Support	47 Ordnance Support	37 NBC Defense
SURVEILLANCE																				13								15			1			*		
• Landing Beach Area																																				
• Enemy Harbor																																				
• U.S. Harbor Protection																																				
• Inshore USW																																				
• USW All Ranges and Depths																													2							
RECONNAISSANCE																				13								15			1			*		
• Beach Area																																				
• Enemy Harbor																																				
• Mining Environment																																				
MINING																				13											1			3,4 8,9		
• Mine Hunting and Countermeasures																																				
• Mine Plants																																				
• Disarm Mine																																				
• Interrogate Mine Fields																																				
NAVIGATION SURVEYS																								14					2					3,4		
RECOVERY																													2		1			+		
• Small Objects																																		16		
• Torpedoes																																				
• Nuclear Weapons																																				
• Space Hardware																																				
• Large Objects																																		6		
FACILITY INSTALLATIONS																													2		1			3,4 18		
• Sonar Array																																				
• Bottom Mounted ULM																																			17	
• Navigation Markers																																				
• Cable Laying and Inspection																																				
• General Constructio.																																				
• Foundation and Bottom																																				
• Tunnels																																				
• Dams																																				
• Wells																																				
SALVAGE																													2		1			3,4 5		
• Ships																																				
• Aircraft																																				
REPAIRS																													1					3		
• In Port																																				
• Underway																																				
SUPPORT																													2					3,4 5,18		
• Oceanographic																																				
• Sub Rescue Personnel																																				
• Undersea Logistics																																				
HABITAT DEVELOPMENT																													2		1			3,4 18		

	DEPTH		TIME		MOBILITY			
UNDERSEA FUNCTIONAL OPERATIONS	Mean Depth	Excursion Depth	Travel Time	Duration of Operation	Speed	Range	Endurance	Object Si
SURVEILLANCE								
• Landing Beach Area	200		H	H_D	3	a	2	s
• Enemy Harbor	200		H	H_D	3	a	2	s
• U.S. Harbor Protection	200		H	D	3		2	s
• Inshore USW	<600		H	D	2		2	s
• USW All Ranges and Depths	All			D				
RECONNAISSANCE								
• Beach Area	200		H_D	H_D	3	a	1	s
• Enemy Harbor	200		H_D	H_D	3	a	1	s
• Mining Environment	200		H_D	H_D	3	a	1	s
MINING								
• Mine Hunting and Countermeasures	<600		H	D	2	a	2	s
• Mine Plants	1000		H	H	2		2	s
• Disarm Mine	<600		H	H	3	a	2	s
• Interrogate Mine Fields	<600		H	D	2	a	2	s
NAVIGATION SURVEYS								
RECOVERY								
• Small Objects	2000		H	D	3	b	2	BE
• Torpedoes	2000		H	D	3	b	2	s
• Nuclear Weapons	2000		H	D	3	b	2	s
• Space Hardware	2000		H	D	3	b	2	ℓ
• Large Objects	2000		H	D	3	b	2	Su
FACILITY INSTALLATIONS								
• Sonar Array	d		D		3	b	2	s
• Bottom Mounted ULM	2000		D		3	b	2	s
• Navigation Markers	2000		H		3	b	2	s
• Cable Laying and Inspection	d		H		3	b	2	s
• General Constructio.	2000		D		3	b	2	s
• Foundation and Bottom	2000		D		3	b	2	s
• Tunnels	2000		D		3	b	2	s
• Dams	<600		D		3	b	2	s
• Wells	2000		D		3	b	2	s
SALVAGE								
• Ships	2000		D		3	b	2	ℓ
• Aircraft	2000		D		3	b	2	ℓ
REPAIRS								
• In Port	100		D		4	b	3	
• Underway	100		H_D		3	b	3	
SUPPORT								
• Oceanographic	All		D		3	b	3	s
• Sub Rescue Personnel	<600				2	b	1	ℓ
• Undersea Logistics	<600		H_D		3	b	3	s
HABITAT DEVELOPMENT					4	b	1	

* 2, 3, 7, 8, 13

\+ 3, 4, 10, 13, 18

Table 11

MISSIONS, OPERATIONS, AND FUNCTIONAL REQUIREMENTS MATRIX

H = hours
D = days
a = less than 100 miles
b = very short, operation independent of range
ℓ = large
s = small
W_W = world wide
1 = very important to success
2 = important to success
3 = not too important to success
4 = unimportant to success

JECTIVES	COMMAND SUPPORT							OPERATIONAL SUPPORT							
UNDERSEA FUNCTIONAL OPERATIONS	32 Naval Communications	33 Electronic Warfare	34 Navigation	35 Ocean Surveillance	36 Reconnaissance and Inte	37 Environmental Systems	38 Special Warfare	41 Logistics	42 Vacant	43 Personnel	44 Astronautic Support	45 Aviation Support	46 Ship Support	47 Ordnance Support	37 NBC Defense
SURVEILLANCE							15			1			*		
• Landing Beach Area															
• Enemy Harbor															
• U.S. Harbor Protection															
• Inshore USW															
• USW All Ranges and Depths								2							
RECONNAISSANCE							15			1			*		
• Beach Area															
• Enemy Harbor															
• Mining Environment															
MINING										1			3,4 8,9		
• Mine Hunting and Countermeasures															
• Mine Plants															
• Disarm Mine															
• Interrogate Mine Fields															
NAVIGATION SURVEYS			14					2					3,4		
RECOVERY								2		1			*		
• Small Objects													16		
• Torpedoes															
• Nuclear Weapons															
• Space Hardware															
• Large Objects													6		
FACILITY INSTALLATIONS								2		1			3,4 18		
• Sonar Array															
• Bottom Mounted CIM														17	
• Navigation Markers															
• Cable Laying and Inspection															
• General Constructio.															
• Foundation and Bottom															
• Tunnels															
• Dams															
• Wells															
SALVAGE								2		1			3,4 5		
• Ships															
• Aircraft															
REPAIRS								1					3		
• In Port															
• Underway															
SUPPORT								2					3,4 5,18		
• Oceanographic															
• Sub Rescue Personnel															
• Undersea Logistics															
HABITAT DEVELOPMENT								2		1			3,4 18		

FUNCTIONAL PERFORMANCE REQUIREMENTS	DEPTH		TIME		MOBILITY			LOAD CARRYING		MANEUVERABILITY		MANIPULATION			SENSING				COGNITION	HARDNESS				COVERTNESS			
UNDERSEA FUNCTIONAL OPERATIONS	Mean Depth	Excursion Depth	Travel Time	Duration of Operation	Speed	Range	Endurance	Object Size	Object Weight	Access Limit	Degree of Freedom	Minimum Skills	Moderate Skills	Complex Skills	Visual	Acoustic	Electromagnetic	Tactile	On Scene Assessment	Mechanical	Radiation	Temperature	Marine Life	Visual	Acoustic	Magnetic	Electrical
SURVEILLANCE																											
• Landing Beach Area	200		H	H_D	3	a	2	s	s						√	√		√	√	√		√	√	√	√	√	√
• Enemy Harbor	200		H	H_D	3	a	2	s	s						√	√	√		√	√		√	√	√	√	√	√
• U.S. Harbor Protection	200		H	D	3		2	s	s										√			√	√				
• Inshore USW	< 600		H	D	2		2	s	s						√	√	√		√	√		√	√	√	√	√	√
• USW All Ranges and Depths	All			D												√			√	√		√	√	√	√	√	√
RECONNAISSANCE																											
• Beach Area	200		H_D	H_L	3	a	1	s	s						√	√		√	√			√	√	√	√	√	√
• Enemy Harbor	200		H_D	H_D	3	a	1	s	s						√	√	√		√	√	√	√	√	√	√	√	√
• Mining Environment	200		H_D	H_D	3	a	1	s	s							√	√		√			√	√	√	√	√	√
MINING																											
• Mine Hunting and Countermeasures	< 600		H	D	2	a	2	s	s			√			√	√	√	√	√	√		√	√	√	√	√	√
• Mine Plants	1000		H	H	2		2	s	s			√			√	√				√		√	√				
• Disarm Mine	< 600		H	H	3	a	2	s	s			√	√	√	√				√	√		√	√	√	√	√	√
• Interrogate Mine Fields	< 600		H	D	2	a	2	s	s			√			√	√	√	√	√	√		√	√	√	√	√	√
NAVIGATION SURVEYS																											
RECOVERY																											
• Small Objects	2000		H	D	3	b	2	BB	5T			√			√	√	√	√	√								
• Torpedoes	2000		H	D	3	b	2	s	s			√			√	√	√	√	√	√		√	√		√	√	√
• Nuclear Weapons	2000		H	D	3	b	2	s	s			√			√	√	√	√	√		√	√	√				
• Space Hardware	2000		H	D	3	b	2	ℓ	ℓ			√			√	√	√	√	√		√	√	√				
• Large Objects	2000		H	D	3	b	2	Sub	1000 T			√	√	√	√	√	√	√	√			√	√				
FACILITY INSTALLATIONS																											
• Sonar Array	d		D		3	b	2	s	s	√		√	√	√	√			√	√			√	√				
• Bottom Mounted CIM	2000		D		3	b	2	s	s	√		√	√	√	√			√	√			√	√	√	√	√	√
• Navigation Markers	2000		H		3	b	2	s	s			√			√	√	√	√	√			√	√				
• Cable Laying and Inspection	d		H		3	b	2	s	s			√	√		√			√	√			√	√	√	√	√	√
• General Constructio.	2000		D		3	b	2	s	s	√		√	√	√	√			√	√			√	√				
• Foundation and Bottom	2000		D		3	b	2	s	s	√		√	√		√			√	√			√	√				
• Tunnels	2000		D		3	b	2	s	s	√		√	√		√			√	√			√	√				
• Dams	< 600		D		3	b	2	s	s	√		√	√		√			√	√			√					
• Wells	2000		D		3	b	2	s	s	√		√	√		√			√	√			√	√				
SALVAGE																											
• Ships	2000		D		3	b	2	ℓ	[illegible]	√		√	√	√	√			√	√			√	√				
• Aircraft	2000		D		3	b	2	ℓ	[illegible]	√		√	√	√	√			√	√			√	√				
REPAIRS																											
• In Port	100		D		4	b	3					√	√	√	√			√	√			√	√				
• Underway	100		H_D		3	b	3					√	√	√	√			√	√			√	√				
SUPPORT																											
• Oceanographic	All		D		3	b	3	s	s			√			√	√		√	√			√	√	√	√	√	√
• Sub Rescue Personnel	< 600				2	b	1	ℓ	ℓ			√	√	√	√	√		√	√			√	√				
• Undersea Logistics	< 600		H_D		3	b	3	s	s			√			√	√		√	√			√	√	√	√	√	√
HABITAT DEVELOPMENT					4	b	1					√	√	√	√	√		√	√			√	√				

Table 11 (concluded)

UNDERSEA FUNCTIONAL OPERATIONS	NWP 22A Doctrine for Amphibious Operations	NWIP 22-1B The Amphibious Task Fr Pl	NWIP 22-4A UDT in Amphibious Operations	NWIP 22-5A The Naval Beach Group	NWIP 23-2B Submarine Support Operations	NWP 24B ASW Operations	NWIP 24-1A ASW Classification Manual	NWP 25 Mobile Logistic Support Operations	NWP 26A Mining Operations	NWIP 26-1 Minefield Planning	NWIP 27A Mine Countermeasures Operations	NWIP 27-1A Support to Mine Countermeasures Operations	NWIP 27-4 Minehunting Procedures	NWIP 29-1 Seal Teams in Sp. War	USN Add 27A Submarine Disaster SAR Operations	NWP 38B Replenishment at Sea	NWP 40A Harbor Defense
SURVEILLANCE																	
• Landing Beach Area	✓		✓	✓	✓				✓	✓	✓	✓		✓			
• Enemy Harbor	✓		✓	✓	✓				✓	✓				✓			
• U.S. Harbor Protection									✓	✓	✓	✓					✓
• Inshore USW	✓		✓			✓			✓	✓				✓			✓
• USW All Ranges and Depths						✓											
RECONNAISSANCE														✓			
• Beach Area	✓		✓	✓	✓				✓	✓	✓	✓		✓			
• Enemy Harbor	✓		✓	✓	✓				✓	✓	✓	✓		✓			
• Mining Environment	✓		✓	✓	✓				✓	✓	✓	✓					
MINING									✓								
• Mine Hunting and Countermeasures	✓		✓								✓	✓	✓				✓
• Mine Plants	✓				✓				✓	✓							✓
• Disarm Mine			✓							✓	✓						✓
• Interrogate Mine Fields										✓	✓	✓					✓
NAVIGATION SURVEYS																	
RECOVERY																	
• Small Objects																	
• Torpedoes																	
• Nuclear Weapons			✓														
• Space Hardware																	
• Large Objects																	
FACILITY INSTALLATIONS																	
• Sonar Array						✓											
• Bottom Mounted ULM																	
• Navigation Markers																	
• Cable Laying and Inspection						✓											
• General Construction																	
• Foundation and Bottom																	
• Tunnels																	
• Dams																	
• Wells																	
SALVAGE																	
• Ships																	
• Aircraft																	
REPAIRS																	
• In Port																	
• Underway																	
SUPPORT																	
• Oceanographic	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
• Sub Rescue Personnel															✓		
• Undersea Logistics	✓	✓	✓	✓		✓		✓								✓	
HABITAT DEVELOPMENT																	

H = hours
D = days
a = less than 100 miles
b = very short, operation independent of range
ℓ = large
s = small
W_W = world wide
1 = very important to success
2 = important to success
3 = not too important to success
4 = unimportant to success

FUNCTIONAL PERFORMANCE REQUIREMENTS

UNDERSEA FUNCTIONAL OPERATIONS	DEPTH		TIME		MOBILITY			LOAD CARRYING		MANEUVERABILITY		MANIPULATION			SENSING				COGNITION	HARDNESS				COVERTNESS			
	Mean Depth	Excursion Depth	Travel Time	Duration of Operation	Speed	Range	Endurance	Object Size	Object Weight	Access Limit	Degree of Freedom	Minimum Skills	Moderate Skills	Complex Skills	Visual	Acoustic	Electromagnetic	Tactile	On Scene Assessment	Mechanical	Radiation	Temperature	Marine Life	Visual	Acoustic	Magnetic	Electrical
SURVEILLANCE																											
• Landing Beach Area	200		H	H_D	3	a	2	s	s						✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓
• Enemy Harbor	200		H	H_D	3	a	2	s	s						✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓
• U.S. Harbor Protection	200		H	D	3		2	s	s										✓			✓	✓				
• Inshore USW	< 600		H	D	2		2	s	s						✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓
• USW All Ranges and Depths	All			D												✓			✓	✓		✓	✓	✓	✓	✓	✓
RECONNAISSANCE																											
• Beach Area	200		H_D	H_D	3	a	1	s	s						✓	✓		✓	✓			✓	✓	✓	✓	✓	✓
• Enemy Harbor	200		H_D	H_D	3	a	1	s	s						✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
• Mining Environment	200		H_D	H_D	3	a	1	s	s							✓	✓		✓			✓	✓	✓	✓	✓	✓
MINING																											
• Mine Hunting and Countermeasures	< 600		H	D	2	a	2	s	s			✓			✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
• Mine Plants	1000		H	H	2		2	s	s			✓			✓	✓				✓		✓	✓				
• Disarm Mine	< 600		H	H	3	a	2	s	s			✓	✓	✓	✓				✓	✓		✓	✓	✓	✓	✓	✓
• Interrogate Mine Fields	< 600		H	D	2	a	2	s	s			✓			✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
NAVIGATION SURVEYS																											
RECOVERY																											
• Small Objects	2000		H	D	3	b	2	BB	5T			✓			✓	✓	✓	✓	✓								
• Torpedoes	2000		H	D	3	b	2	s	s			✓			✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓
• Nuclear Weapons	2000		H	D	3	b	2	s	s			✓			✓	✓	✓	✓	✓		✓	✓	✓				
• Space Hardware	2000		H	D	3	b	2	ℓ	ℓ			✓			✓	✓	✓	✓	✓		✓	✓	✓				
• Large Objects	2000		H	D	3	b	2	Sub	1000 T			✓	✓	✓	✓	✓	✓	✓	✓			✓	✓				
FACILITY INSTALLATIONS																											
• Sonar Array	d		D		3	b	2	s	s	✓		✓	✓	✓	✓			✓	✓			✓	✓				
• Bottom Mounted ULM	2000		D		3	b	2	s	s	✓		✓	✓	✓	✓			✓	✓			✓	✓	✓	✓	✓	✓
• Navigation Markers	2000		H		3	b	2	s	s			✓			✓	✓	✓	✓	✓			✓	✓				
• Cable Laying and Inspection	d		H		3	b	2	s	s			✓	✓		✓			✓	✓			✓	✓	✓	✓	✓	✓
• General Construction	2000		D		3	b	2	s	s	✓		✓	✓	✓	✓			✓	✓			✓	✓				
• Foundation and Bottom	2000		D		3	b	2	s	s	✓		✓	✓		✓			✓	✓			✓	✓				
• Tunnels	2000		D		3	h	2	s	s	✓		✓	✓		✓			✓	✓			✓	✓				
• Dams	< 600		D		3	b	2	s	s	✓		✓	✓		✓			✓	✓			✓	✓				
• Wells	2000		D		3	b	2	s	s	✓		✓	✓		✓			✓	✓			✓	✓				
SALVAGE																											
• Ships	2000		D		3	b	2	ℓ	✓	✓		✓	✓	✓	✓			✓	✓			✓	✓				
• Aircraft	2000		D		3	b	2	ℓ	✓	✓		✓	✓	✓	✓			✓	✓			✓	✓				
REPAIRS																											
• In Port	100		D		4		3					✓	✓	✓	✓			✓	✓			✓	✓				
• Underway	100		H_D		3	b	3					✓	✓	✓	✓			✓	✓			✓	✓				
SUPPORT																											
• Oceanographic	All		D		3	b	2	s	s			✓			✓	✓		✓	✓			✓	✓	✓	✓	✓	✓
• Sub Rescue Personnel	< 600		H_D		2	b	1	ℓ	ℓ			✓	✓	✓	✓	✓		✓	✓			✓	✓				
• Undersea Logistics	< 600		H_D		3	b	3	s	s			✓			✓	✓		✓	✓			✓	✓	✓	✓	✓	✓
HABITAT DEVELOPMENT					4	b	1					✓	✓	✓	✓	✓		✓	✓			✓	✓				

● 3, 4, 8, 9, 13
† 3, 1, 10, 13, 18

requirements are estimated on a graduated number scale where 1 is very important to success, 2 and 3 are less important, and 4 is very unimportant. Range is estimated in two ways: (1) the range is less than 100 miles or (2) the range is relatively short--i.e., the operation is independent of range. Reference 9 provides an assessment of ranges under 100 miles for particular strike warfare operations in those world areas where reconnaissance and surveillance are more probable. Using these ranges, it was computed that, in 80% of the areas, the range from the 33-fathom line (200 feet) to the beach is 40 miles or less. In 50% of the areas, 10 miles or less is the range to the 33-fathom line. With respect to the object weight and size under load-carrying ability, only two categories for estimated weight are used; small, which is 5 tons or less, and large, which is 10 tons or greater.

V ALTERNATIVES TO MISSION ACCOMPLISHMENT

A. General

Man's interest and concern with the sea and his excursions into the sea date back to earliest recorded history. It was not until recent years however, that substantial gains in undersea technology and in the understanding of high pressure physiology have allowed man to make significant long term excursions into the sea.

There are two techniques for placing man in the sea. The first, the MAN-IN-THE-SEA concepts, places man in direct contact with his working environment and leaves him completely exposed to the ambient ocean pressure. The ultimate goal of this development is to enable man to move about the ocean depths with freedom comparable to that which he enjoys on land. The second, the alternatives to the MAN-IN-THE-SEA concepts, provides a surface atmospheric environment, often within a protective shell, which shields man from the ambient undersea environment. Free swimming deep submergence vehicles have carried men to the deepest known ocean areas. The major drawback of such systems is that man is separated from the task he must perform. However, improvements are being made in underwater sensors and mechanical manipulators to provide the shielded man with better contact with his work environment.

Advances in the MAN-IN-THE-SEA concepts are placing man at greater ocean depths and allowing him to stay longer at such depths to accomplish useful work. On the other hand, the systems that shield man from the ambient ocean environment can now penetrate extreme ocean depths and their work capabilities are improving. The capabilities of the MAN-IN-THE-SEA concepts and the alternative systems therefore are becoming competitive from a functional veiwpoint. The identification of naval missions that can be accomplished by MAN-IN-THE-SEA concepts must consider the capabilities of alternatives that can accomplish the same mission.

B. Description of Alternatives

1. MAN-IN-THE-SEA Concepts

MAN-IN-THE-SEA concepts are defined broadly as those underwater systems where man is exposed to the ambient pressure environment.

Therefore, it is nothing more than a new name assigned to the field of diving technology. The development of compressed gas diving technology progressed from the tethered hard-hat diving techniques, through the untethered self-contained underwater breathing apparatus (SCUBA) techniques, and finally to the saturation diving techniques.

The development of saturation diving techniques has created a potential for sending an unshielded man to heretofore unattainable depths and for long term habitation of the sea in the ambient pressure environment. Long term undersea habitation and accomplishment of meaningful work at great ocean depths are the objectives of such research efforts as: (1) the U.S. Navy sponsored SEALAB test series, (2) the CONSHELF test series by Cousteau of France, and (3) the MAN-IN-THE-SEA series by Link (Ocean Systems, Inc.) of the United States. The requirements of off-shore oil drilling operations--e.g., well-head completion, drilling rig and pipeline repair, and equipment salvage--gave impetus to the rapid transformation of saturation diving techniques from experimental stages to operational commercial applications. In recognition of the military potential of saturated diving techniques, the U.S. Navy is supporting a MAN-IN-THE-SEA program. This program is directed toward establishing man's ability to accomplish useful work down to the continental shelf depth and to determine man's ultimate depth-time limits in the ambient ocean environment. The completed SEALAB I and II operations and the upcoming SEALAB III operation are one aspect of the total Navy MAN-IN-THE-SEA program.

A comprehensive review of the MAN-IN-THE-SEA concepts is provided in Appendix A. This review considers (1) the basic philosophy of diving technology, (2) the current status of diving technology, (3) the direction or focus of current R&D efforts, and (4) the possibility of advanced diving techniques, such as fluid breathing. The major classes of MAN-IN-THE-SEA concepts are summarized here to provide the background for comparing the capabilities of alternative systems. In addition to reviewing the MAN-IN-THE-SEA concepts, the project team reviewed the reported results of diver performance studies and consolidated essential data from those studies. The review of diver performance studies is presented in Appendix B and is organized into four performance areas: (1) psychomotor performance, (2) mental task performance, (3) sensation and perception, and (4) communications.

There are many alternatives in the use of diving techniques. In general, diving operations can be divided into two basic modes: the free swimming man and the tethered man. Tethered diving operations in turn can be subdivided into the following modes: (1) the direct surface-tethered man, (2) the indirect surface-tethered man, (3) the fixed

bottom-site tethered man, and (4) the mobile vehicle-tethered man. These various modes of diving operation are illustrated in Figure 9, which clarifies the division of the modes of operation.

2. Alternatives to MAN-IN-THE-SEA Concepts

The alternatives to MAN-IN-THE-SEA concepts include (1) manned free-swimming vehicles, (2) manned-tethered vehicles, (3) unmanned or remote-controlled tethered vehicles, and (4) manned fixed bottom stations. Many vehicle-oriented systems have been designed to accomplish undersea tasks. A comprehensive list and description of the systems that are available throughout the world are contained in Reference 10. Selected examples of these systems are described in the following paragraphs.

a. Manned Free-Swimming Vehicles

The manned free-swimming vehicles constitute the largest group of alternatives to MAN-IN-THE-SEA concepts. More than 30 manned submersibles are being used in the United States by the Navy, other governmental agencies, and commercial operators to accomplish undersea tasks. Specific examples of this class of alternatives that were selected for comparative analysis are the ALVIN, AUTEC, and BEAVER MK IV vehicles. General characteristics of these vehicles are provided in Figures 10 through 12.

The ALVIN, which is operated by the Woods Hole Oceanographic Institute under contract to the Office of Naval Research, is performing a wide spectrum of undersea activities. These activities include (1) inspection of underwater instruments and structures at the Navy's Atlantic Undersea Test and Evaluation Center off Andros Island (2) oceanographic surveys requiring bottom and water samples; coring; placing and retrieving instruments and markers; photographing; and so forth. The ALVIN was used successfully during the search and location of the hydrogen bomb that was lost near Palomares, Spain. This vehicle is equipped with a mechanical manipulator that can handle specialized tools for accomplishing underwater tasks--for example, the bottom coring tools used in the oceanographic survey activities. The manipulator has a grapple hand terminal device that can handle a variety of specially designed tools and instruments. Sensory equipment on the ALVIN includes scanning sonar, echosounder, navigational sonar, television cameras, and movie cameras. Communications equipment includes acoustic communications for underwater use and radio communications for surface use.

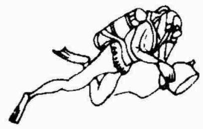
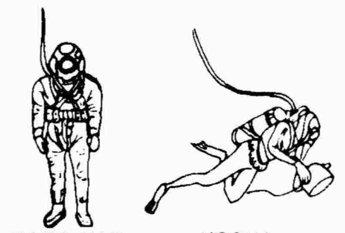
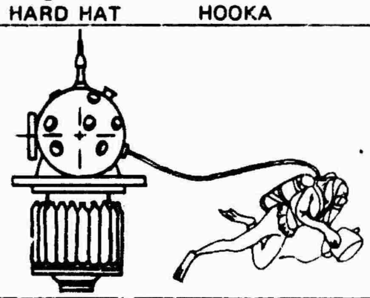
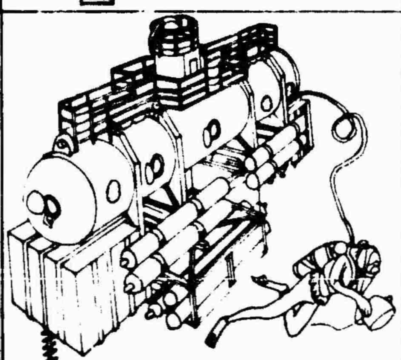
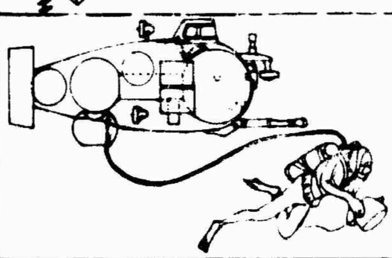
MODES		EXAMPLES	
FREE SWIMMING MAN			
TETHERED MAN	DIRECT SURFACE TETHER	 HARD HAT HOOKA	
TETHERED MAN	INDIRECT SURFACE TETHER		• U.S. NAVY DDS MARK I AND MARK II • OCEAN SYSTEMS, INC. ADS • WESTINGHOUSE CACHELOT
TETHERED MAN	FIXED BOTTOM-SITE TETHER		• U.S. NAVY SEALAB I, II, III • COUSTEAU CONSHELF I, II, III • EDWIN LINK MAN-IN-SEA
TETHERED MAN	MOBILE VEHICLE TETHER		• NORTH AMERICAN ROCKWELL BEAVER MARK IV • OCEAN SYSTEMS, INC. DEEP DIVER • LOCKHEED DEEP QUEST

Figure 9 MODES OF DIVING OPERATIONS

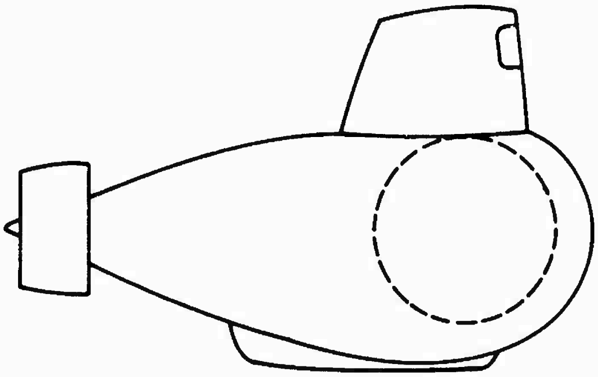
CONFIGURATION	CHARACTERISTICS	
	DEPTH 6,000 feet LIFE SUPPORT 8 hours normal 24 hours maximum SPEED 2 knots cruise 6 knots maximum	RANGE 20–25 nautical miles DIMENSIONS Length: 22 feet Width: 8 feet Height: 12 feet PAYLOAD 1,200 pounds CREW 2

Figure 10 CONFIGURATION AND CHARACTERISTICS OF ALVIN

The AUTEC vehicle is essentially a second generation version of the ALVIN. Two of these vehicles, AUTEC I and AUTEC II, are being built for the Navy Ship Systems Command. They are intended for use at the Navy's Andros Island operation. The vehicles are to be used for placing electronic systems on the ocean bottom and inspecting, testing, and retrieving them and for performing oceanographic research. The vehicles also will be capable of conducting or assisting in salvage operations at depths to 6,500 feet. As currently visualized, each vehicle will be equipped with two mechanical manipulators of more advanced design than that of the ALVIN (see Appendix C). Sensory and communications equipment are essentially the same as those on the ALVIN.

The BEAVER MARK IV submarine work boat was constructed by North American Rockwell Corporation to be used in supporting off-shore oil exploration, drilling, and production operations. The vehicle is equipped with an advanced design manipulator that can handle a variety of tools. The tools, which can be changed underwater, include impact wrenches, stud guns, jet pumps, wire brushes, grinding wheels, and cable cutters. The BEAVER also serves as a mobile platform for MAN-IN-THE-SEA operations, since it contains a diver lock-in/lock-out capability. Sensory and communications equipment are essentially the same as those on the ALVIN and AUTEC vehicles.

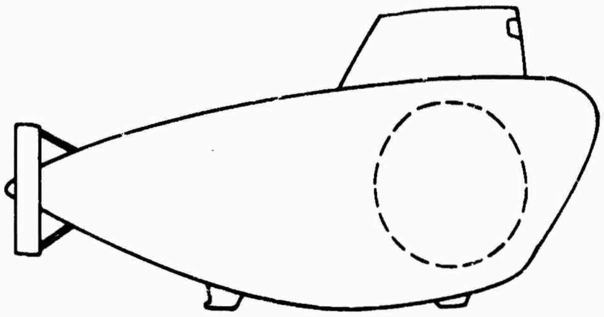
CONFIGURATION	CHARACTERISTICS	
	DEPTH 6,500 feet LIFE SUPPORT SPEED 2 knots cruise 8 knots maximum RANGE 20–25 nautical miles	DIMENSIONS Length: 25 feet Width: 10 feet Height: 15 feet PAYLOAD 1,200 pounds CREW 2

Figure 11 CONFIGURATION AND CHARACTERISTICS OF AUTEC

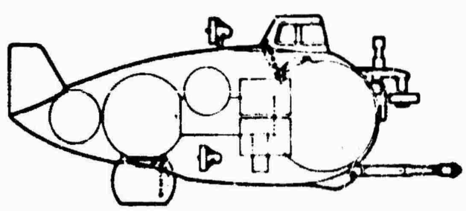
CONFIGURATION	CHARACTERISTICS	
	DEPTH 2,000 feet LIFE SUPPORT 36 hours SPEED 2.5 knots cruise 5.0 knots maximum RANGE 20–25 nautical miles	DIMENSIONS Length: 24 feet Width: 10 feet Height: 11 feet PAYLOAD 2,000 pounds CREW 2 operators 3 divers

Figure 12 CONFIGURATION AND CHARACTERISTICS OF BEAVER MARK IV

b. Manned Tethered Vehicles

Two examples of manned tethered vehicles were selected for comparative analysis during this study.

The first, which is shown in Figure 13, is an articulated metal diving dress. It consists of (1) a body formed of three spherical zones superimposed with extensions for the top, arms, and legs; (2) a spherical dome cover; (3) two articulated arms connected to the body through a gimbal spherical articulator, which has revolving joints above the elbow and two pairs of pliers (or other interchangeable tools); (4) two articulated legs for propulsion; (5) a ballast chamber on the back of the body; and (6) two compressed air bottles for serving the ballast chamber and two oxygen bottles for life support. The first metal suit was built in 1935. Since that time, more advanced versions have been constructed. The suit is sold commercially by Robert Galeazzi, Ltd, La Spesia, Italy.

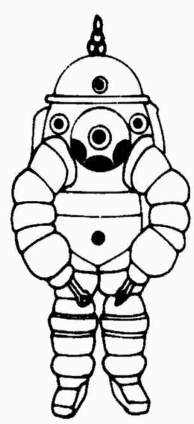
CONFIGURATION	CHARACTERISTICS
	DEPTH 600 feet LIFE SUPPORT 3 hours SPEED RANGE DIMENSIONS Length: Width: 4 feet Height: 8 feet PAYLOAD CREW 1

Figure 13 CONFIGURATION AND CHARACTERISTICS OF ARTICULATED METAL DIVING DRESS

The second example of a manned tethered vehicle is the Guppy which is built by Sun Shipbuilding and Dry Dock. This vehicle, which is shown in Figure 14, is a two-man craft tethered to a support ship or oil rig by a 3,000 foot electrical cable. Its unique feature is the availability of 16 killowatts of high intensity light. Although descriptive data on the vehicle do not specify manipulative capability, there is no reason to assume that manipulators cannot be mounted on it.

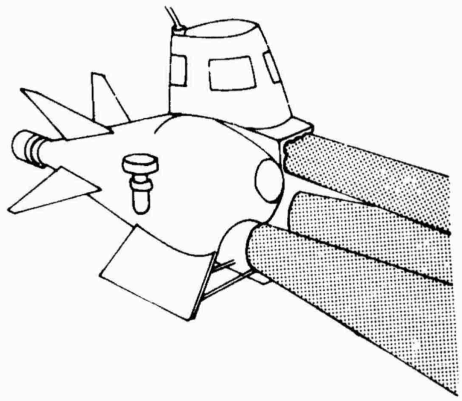
CONFIGURATION	CHARACTERISTICS
	DEPTH 3,000 feet LIFE SUPPORT 8 hours SPEED 5 knots RANGE Unlimited DIMENSIONS Length: 20 feet Width: 6 feet Height: 9 feet PAYLOAD CREW 2

Figure 14 CONFIGURATION AND CHARACTERISTICS OF GUPPY

c. Unmanned Remote-Controlled Vehicles

Two examples of unmanned remote-controlled vehicles are the CURV vehicle and MOBOT. CURV (cable-controlled underwater research vehicle) was developed by the U.S. Naval Ordnance Test Station, Pasadena, California. CURV weighs about one ton and operates to depths of about 2,000 feet. Advanced versions should be able to reach 6,000 feet, however. The vehicle was designed to recover torpedos and other hardware weighing a maximum of one ton. The CURV vehicle, which is shown in Figure 15 is operated by a five-man crew on the surface. This crew directs, controls, and monitors recovery operation through a closed-circuit television network, supported by acoustic detection and positioning components.

The MOBOT (MObile roBOT) was developed by Hughes Aircraft Company and is used by Shell Oil Company of California as an underwater wellhead manipulator. MOBOT, which is shown in Figure 16, consists of an electro-hydraulic vehicle designed to be lowered into the ocean, land on a track, and operated to insert or break out screws arranged in a horizontal axis. The MOBOT's operations are directed from the surface by means of a closed-circuit television network supported by acoustic sensors. MOBOT, because of the nature of the work it must perform, is very specialized and therefore is limited with respect to the underwater work it can perform. A more advanced version of MOBOT has been proposed but to date has not been constructed. This advanced vehicle called UNUMO is also shown in Figure 16.

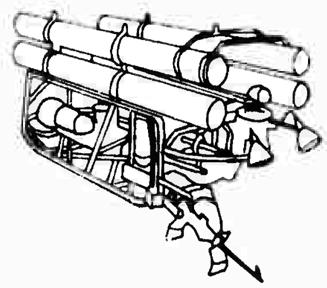
CONFIGURATION	CHARACTERISTICS
	DEPTH 2,000 feet LIFE SUPPORT None SPEED 2–3 knots RANGE Unlimited DIMENSIONS Length: 13 feet Width: 5 feet Height: 6 feet PAYLOAD 2,000 pounds CREW None

Figure 15 CONFIGURATION AND CHARACTERISTICS OF CURV

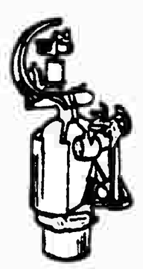
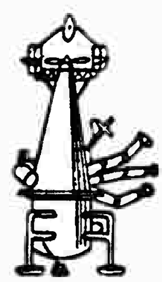
CONFIGURATION	CHARACTERISTICS
 MOBOT  UNUMO	DEPTH 1,000 feet LIFE SUPPORT None SPEED 2–3 knots RANGE Unlimited DIMENSIONS Length: Width: 6 feet Height: 14 feet PAYLOAD CREW None

Figure 16 CONFIGURATION AND CHARACTERISTICS OF MOBOT

d. <u>Fixed Bottom Station</u>

In studies conducted for the U.S. Naval Civil Engineering Laboratory, Port Hueneme, California, three concepts of fixed bottom stations were proposed. These studies defined the most suitable configurations and power supplies for a manned underwater station, capable of supporting the requirements of five individuals, both in life support systems and laboratory spaces. Personnel could remain in the station at depths down to 6,000 feet for 30 days. The three concepts were proposed by General Dynamics Corporation, Groton, Connecticut;[11] Southwest Research Institute, San Antonio, Texas;[12] and Westinghouse Electric Corporation, Baltimore, Maryland.[13] The General Dynamics version is shown in Figure 17. The station would provide an atmospheric environment in which men could live and perform oceanographic research via remote control sensors, instruments, and manipulators.

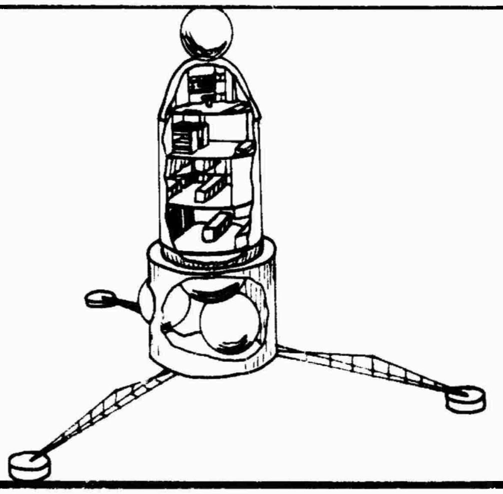
CONFIGURATION	CHARACTERISTICS	
	DEPTH 6,500 feet LIFE SUPPORT 30 days SPEED RANGE	DIMENSIONS Length Width Height PAYLOAD CREW 5

Figure 17 CONFIGURATION AND CHARACTERISTICS OF FIXED BOTTOM STATION

VI DEFINITION OF MAN-IN-THE-SEA MISSIONS

A. General

The approach taken in this study to define MAN-IN-THE-SEA missions was directed toward answering the following questions:

- What are the unique capabilities of the unshielded man in accomplishing specific underwater tasks?

- Which Navy undersea missions have essential tasks that require the unique capabilities of the unshielded man?

These fundamental questions were answered (1) by conducting a comparative analysis of alternative capabilities that identified the unique capabilities of the unshielded man and (2) by isolating the functional operations with associated tasks that require the unique capabilities of the unshielded man. The resulting set of MAN-IN-THE-SEA missions are summarized in Section VI.

B. Comparative Analysis of Capabilities

The alternative systems for accomplishing Navy undersea missions described in Section V are summarized in Table 12. These alternative systems served as the basis for the comparative analysis of capabilities. Since they reflect current capabilities, whereas this study addresses the 1975-85 era, the project team had to project the future capabilities. Therefore, in the comparative analysis that follows, current R&D efforts are reviewed briefly and their effects on future systems capabilities are assessed.

1. Depth Capabilities.

Even by the most optimistic estimates of advanced diving technology, the depth an unshielded man can reach is very limited relative to that which can be reached using the shielded systems approach. Technological and physiological factors limit the depth an unshielded man can reach (see Appendix A). There may be some psychological limits as well, but they are considered to be secondary in importance.

Table 12

SUMMARY OF ALTERNATIVE SYSTEMS FOR MISSION ACCOMPLISHMENT

Alternative System			Example
MAN-IN-THE-SEA Concepts	Free Swimmer		SCUBA Divers
	Tethered Man	Direct Surface Tether	Hard Hat Divers, Hooka Divers
		Indirect Surface Tether	Advanced Diving System (ADS) MARK I CACHELOT Westinghouse
		Habitat Tether	SEALAB CONSHELF, MAN-IN-THE-SEA
		Vehicle Tether	Deep Diver Vehicle BEAVER MARK IV VEHICLE
Alternatives to MAN-IN-THE-SEA Concepts	Manned Free Vehicle		ALVIN, AUTEC, BEAVER MARK IV
	Tethered Vehicle	Manned Tethered Vehicle	Articulated Diving Dress, GUPPY Vehicle
		Unmanned Tethered Vehicle	CURV, MOBOT, UNUMO
	Fixed Bottom Station		NCEL, Port Hueneme

The principal technological factors affecting man's depth capability are (1) the limitations in life support equipment and (2) the limited ability to control and monitor critical mixed-gas breathing atmospheres. The first limitation constrains the depth that a free swimmer can reach and still have sufficient endurance to accomplish useful work. The present solution to this limitation is the use of the tethering technique, in which man is connected by a hose to a larger gas supply on the surface, on a vehicle, or in a bottom station. The problem of limited gas supply might be overcome by such concepts as cryogenic gas storage and the extraction of oxygen from seawater (artificial gills). Development of improved gas analysis techniques would overcome the second technological limitation on depth.

The physiological factors that limit the depth to which man can descend stem from the indirect and direct effects of hydrostatic pressure. The principal indirect effects of pressure are increased gas density, oxygen toxicity, and inert gas toxicity effects in breathing. As gas density increases with increased pressure (depth), the effort required to breathe increases proportionally. It is quite conceivable that this effort would be equal to a significant amount of man's work output. A technological solution to the gas density problem would be to provide a breathing pump or active ventilation assistance. While the biochemical effects that lead to oxygen toxicity are still not clearly understood, they can be minimized by careful control of the oxygen content in the breathing environment. This control is a technological factor mentioned earlier. As with oxygen toxicity, the exact biochemical effects resulting in inert gas toxicity are not understood. The current solution to reducing the effects of inert gas toxicity is to use multiple gas mixtures, helium-nitrogen-oxygen, and even hydrogen in the breathing mixtures. The fluid breathing concept currently being explored is a very intriguing solution to the inert gas toxicity problem. In this concept, oxygen enriched fluid is used to fill the lungs, thus eliminating the need for inert gas. While this concept is still in a very early research stage, successful tests have been made with animals.* The direct effects of pressure on the cellular structure of the human body also limit the depth that man is able to endure. Although data are not available on human cellular tolerance to pressure, some effects of pressure on human skeletal structure have been indicated and some early experiments on animals

* Recent unconfirmed reports indicate that human volunteers have been used in successful experiments in which half the lung was filled with fluid.

have indicated that pressure affects the central nervous system. Looseness of joints at depths exceeding 500 feet has been reported; divers' arms and legs slip out of joint rather easily at these depths. At depths greater than 1,000 feet, there appear to be some effects on the cellular structures. It has been demonstrated that the direct effects of pressure include: (1) failure of cell division, (2) failure of ameboid movement, (3) inhibition of biological luminescense, and (4) inhibition of growth of bacteria. Bacterial growth is inhibited by the pressures at 1,000 feet of seawater. To date, man has reached a depth of slightly over 1,000 feet. It is important to note that there is no information on the long term effects of inhibited bacterial growth at these depths. Conservative estimates of physiologists who have worked with diving technology place man's depth limit from 1,250 feet to 1,500 feet. The most optimistic estimates place the limit from 1,500 to 3,000 feet.

In addition to the maximum depth limit, a diver is limited in his ability to vary depth during the work cycle. This limitation is imposed by the need for decompression (see Appendix A). The actual excursion depth limit during a working dive is still not well-defined and is being investigated by physiologists.

Compared with MAN-IN-THE-SEA concepts, even the current operating vehicles have exceeded by a factor of two, the most optimistic estimates of unshielded man's depth limit. In many cases, the depth that a vehicle system can achieve is limited only by economic considerations. With the exception of the BEAVER MARK IV--which was designed to satisfy the requirements of off-shore oil operations and is only capable of achieving a depth of 2,000 feet--most free vehicles are designed for depths around 6,000 feet. A 6,000-foot depth capability allows these vehicles to reach about 30% of the ocean bottom. Vehicles that are capable of penetrating the deepest ocean depths are in existence, and more advanced and versatile vehicles are being designed and constructed. Tethered vehicles, such as MOBOT, are generally limited by tether length. An advanced design CURV is being developed that can approach 6,000 feet.

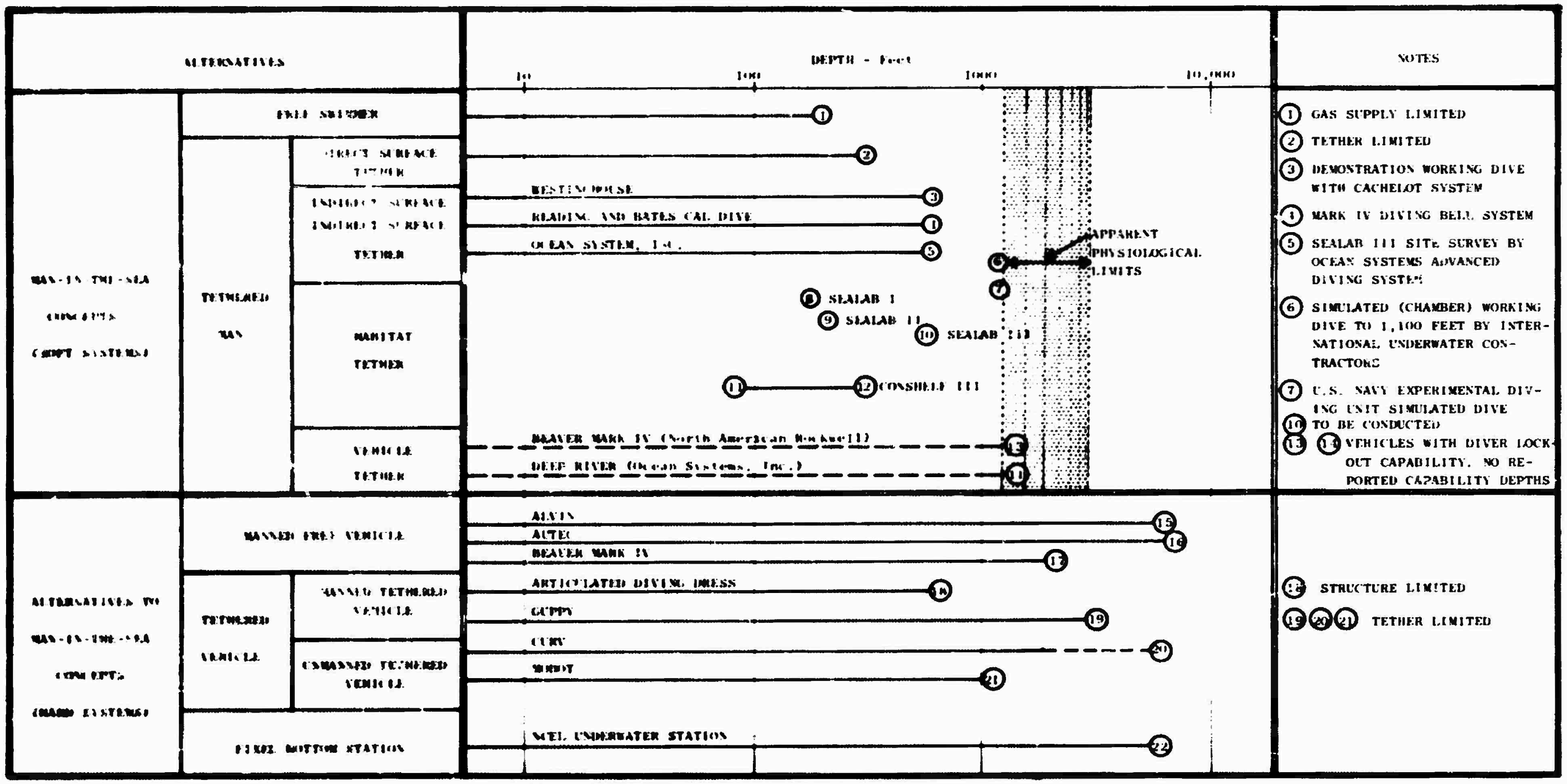
Table 13 provides a summary of the depth capabililies of alternative systems. In the case of the MAN-IN-THE-SEA concepts, some examples of depths reached are shown to indicate the depth penetrated by unshielded man.

2. Time Capability

The time capability of MAN-IN-THE-SEA concepts is described in terms of total bottom time and water immersion time. Since the development of saturation diving technique, the time an unshielded man can stay in ambient

Table 13

SUMMARY OF DEPTH CAPABILITIES OF ALTERNATIVES



pressure--i.e., the bottom time--was increased by several orders of magnitude. A primary objective of research efforts, such as the Navy SEALAB operations, is to determine the exact length of time that man can exist in a hydrostatic pressure environment. Long term effects of prolonged exposure to high hydrostatic pressure are practically unknown at this time. In the few experiments to date, no ill effects have been apparent. The depth-time relationships of long term undersea habitation experiments, both completed and planned, are summarized in Figure 18.

Water immersion time refers to the length of time a diver actually spends in the water, which is limited primarily by water temperature and the effects of water on human skin. The first, the effects of water temperature, can be avoided by providing heated diving suits for divers. A nuclear isotope powered, hot water heated suit will be tested during the SEALAB III operations. There should be no water immersion time limit for a diver who is provided with a heated suit. The effects of prolonged water immersion on human skin is under study. Although no data on immersion limits have been found, it would appear that man's capability to withstand immersion could be enhanced by surrounding him with a protective fluid.

In comparison, it would appear that the time capability of MAN-IN-THE-SEA concepts is comparable to the vehicle-oriented systems to depths approaching 600 feet. More must be known, however, about the long term effects of pressure at greater depths. Immersion time for the unshielded man should be unlimited if adequate protective dress can be provided; this factor does not appear to be a technological limitation. The operating time of free vehicles is limited by life support and power source endurance capabilities. The primary constraint is in the endurance limitation of conventional power sources. Compact nuclear power package would eliminate current vehicle endurance limits. Similarly, fixed bottom habitat is power source limited.

3. Mobility Capability

Since the movements of the tethered man and the tethered vehicles are constrained by the tether, the comparison of mobility considers only the capabilities of the free swimmer and the free vehicle. This comparison is shown in Figure 19. The shaded area in the figure identifies the speed-range capability of a free swimmer propelled by swim fins and carrying life support equipment equivalent to the size of three, 72-cubic foot capacity SCUBA tanks. The upper bound is the endurance capability for a trained athlete. The curve is generated from data published in Reference 14. In comparison, the published speed-range capability of BEAVER MARK IV and ALVIN are indicated in the figure. The vehicles have a distinct

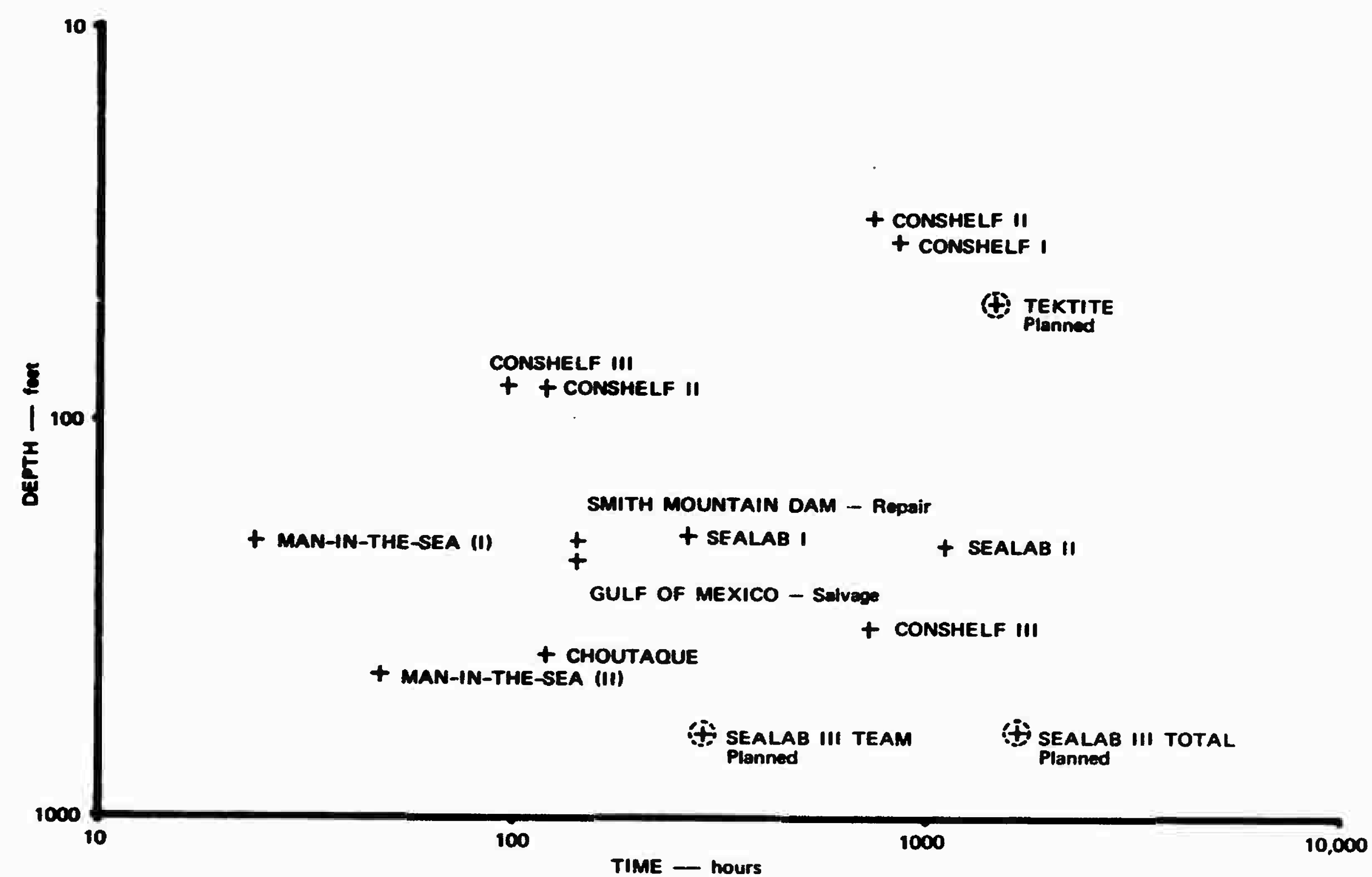


Figure 18 COMPLETED AND PLANNED PROLONGED SUBMERGENCE EXPERIMENTS

advantage over man. Furthermore, since man's speed-range capability is limited by a physical constraint whereas the vehicle capabilities are limited by power source technology, the gap between man and vehicle capabilities will increase.

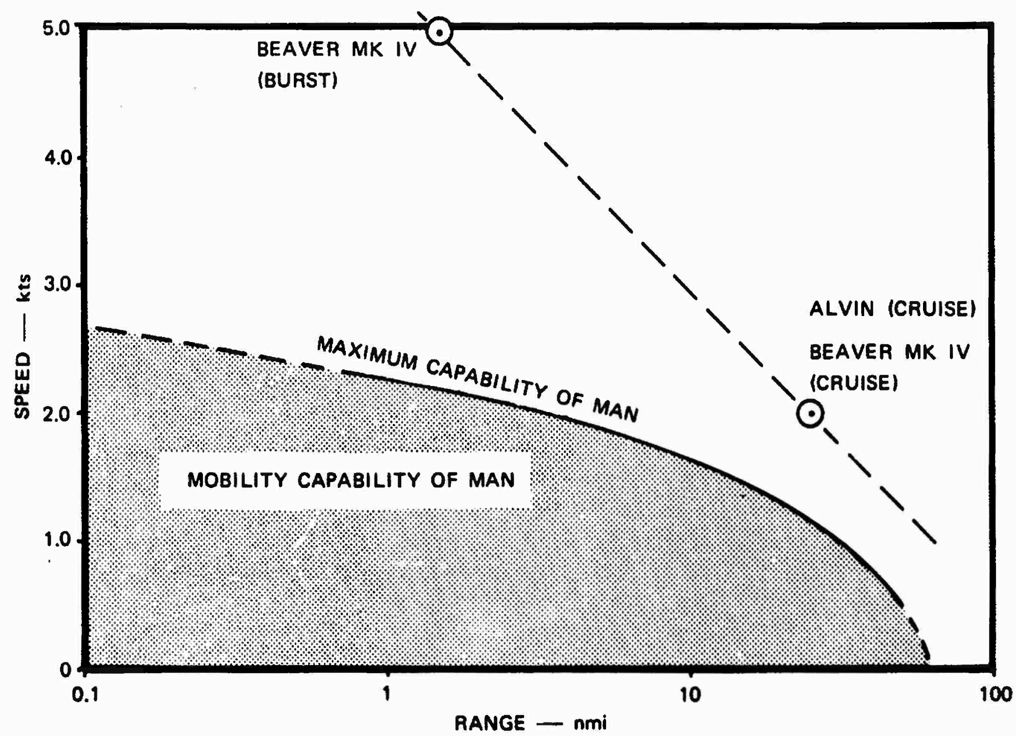


Figure 19 SPEED-RANGE COMPARISON OF MAN AND VEHICLES

4. Load-Carrying Capability

On the basis of the in-water weight of loads that must be picked up and transported, vehicles will always have an advantage over unaided man. A rough estimate of load-carrying capability is 20 pounds for a man and 2,000 pounds for a vehicle, making the vehicle advantage over man a factor of 100. If the comparison is made on the basis of using buoyant life devices, the vehicle will again have the advantage. Since the vehicles have a mobility advantage, they will also have a load-carrying advantage.

5. Maneuverability

No analysis is necessary to state that man has the advantage in maneuverability. Man is very compact and agile and can enter limited access spaces and maneuver around congested structures. It is difficult

to visualize vehicles, manned or unmanned, that can approach the compactness and agility of man in accomplishing undersea tasks.

6. Manipulative Capability

The comparison of manipulative capabilities of man and mechanical manipulators on vehicles is made difficult by the lack of clearly defined performance measures. There is no quantitative measure of dexterity nor is there a clear-cut definition of manipulative success or failure. Furthermore, the comparison is complicated by the availability of a wide range of diver tools and mechanical manipulator terminal devices. The comparison made in this study therefore is a very general assessment and results in a qualitative statement of manipulative capability.

As the basis for comparing the capabilities of man and mechanical manipulators, the level of manipulative skills required to accomplish specific underwater tasks was defined as shown in Table 14. A review of available data on diver manipulative performance was conducted and the results are reported in Appendix B. Available descriptive data concerning the capabilities of underwater mechanical manipulators also were reviewed, and a summary is provided in Appendix C. The following conclusions were drawn from the comparison of man and mechanical manipulators:

a. Manipulative tasks that require minimum manipulative skills can be accomplished equally well by man and mechanical manipulators.

b. Manipulative tasks that require moderate manipulative skills can be accomplished by man and by a mechanical manipulator if the latter is "given enough time." On the basis of very few data, it is estimated that mechanical manipulators will take 10 to 100 times as long to accomplish a task depending on the complexity of the task. For example, a simple connecting/disconnecting task might take a man 5 seconds to accomplish, whereas a manipulator will require a minute, or, a more complex bolting task might take a man 10 seconds and a manipulator 5 minutes.

c. Manipulative tasks that require complex manipulative skills can be accomplished only by man.

For further comparison, the tools and terminal devices available for accomplishing underwater tasks are listed in Table 15.

Additional important manipulative advantages of man over the mechanical manipulators are the dynamic range of man's manipulative capability,

Table 14

SUMMARY OF REQUIRED MANIPULATIVE SKILLS

Manipulative Tasks	Degree of Manipulative Skill Required: Minimum	Moderate	Complex
Cutting		X	
• Sawing		X	
• Shearing		X	
• Burning			X
• Pyrotechnics			X
Torqueing		X	
Hammering	X		
Drilling		X	
Punching		X	
Stud Driving		X	
• Riveting		X	
• Fastening		X	
Sealing		X	
• Crimping		X	
• Vacuumizing		X	
Welding			X
Coring		X	
Calking/Coating		X	
Guiding/Positioning		X	
Connecting/Disconnecting	X		
De-embedding	X		
• Raising	X		
• Dislodging	X		
• Excavating	X		

Source: Reference 15.

his flexibility, and his reliability. Dynamic range refers to the size of jobs a man can handle. For example, a man can easily manipulate objects smaller than 0.1 inch to objects up to sizes measured in feet. Various sizes of mechanical manipulators are generally required to handle the range of objects that man can handle. Flexibility refers to the range of jobs that a man can handle. For example, a man can use an unlimited range of tools compared with the mechanical manipulators (Table 15). Furthermore, man has the flexibility to use improvised tools on the job site when an unexpected situation arises whereas mechanical manipulators with specialized terminal devices are not as flexible. Reliability refers to the ability to accomplish a specific manipulative task without error--for example, dropping components, such as nuts, bolts, and even tools, during a job. Although reliability is somewhat difficult to measure, it is generally agreed that man is a much more reliable manipulator than the mechanical devices.

7. Sensing Capabilities

The principal sensory advantage of MAN-IN-THE-SEA concepts is the availability of tactile senses. The visual capability of man in the water (see Appendix B) and that of man in a vehicle are comparable. Because of the larger payload capability of vehicles, which allows the use of acoustic and electromagnetic sensing devices, the vehicles would normally have the advantage in sensory capabilities. The hearing of man in the water shows some spectral degradation, and at higher frequencies (above 3,000 Hz) there is a complete loss of sound localization capability.

8. Cognitive Skills

In the undersea environment, the cognitive skills of unshielded man show some degradation, which is attributed to inert gas toxicity and to some extent to stress imposed by the hostile ocean environment. If inert gas toxicity problems can be resolved through the use of advanced diving techniques, such as fluid breathing, then the cognitive skills or on-site assessment capability of unshielded man could be equivalent to that of a man in the protective shell of a vehicle.

9. Hardness

With respect to hardness, the vehicle-oriented systems have the advantage over the MAN-IN-THE-SEA concepts for protecting man from mechanical (explosions), radiation, temperature (cold), and marine life hazards.

Table 15

AVAILABLE HAND AND MECHANICAL MANIPULATOR TOOLS

Tasks	Tools																																																		
	Saw-Powered	Saw-Hand	Saw-Zero Reaction	Shears	Open and Box Wrenches	Adjustable Wrench	Ratchet Wrenches	Power Wrench-Impact	Wrench-Zero Reaction	Screwdriver	Ratchet Screwdriver	Screwdriver-Zero Reaction	Hammer-Hand	Hammer-Electromotive	Drill-Powered	Drill-Hand	Drill-Zero Reaction	Punch-Magnetomotive	Punching Head	Riveter-Magnetic	Stud Gun and Fastener	Crimping Tool	Vacuum Tool	Electron Beam Gun	Arc/Oxygen	Oxygen-Hydrogen	Metal/Arc Torch	Coring Kit	Guide Pins	Coupling Fasteners	Slings and Rigging Gear	Clamps	Ice Tongs-Clam Grip	Jacks and Levers	Winches and Hoist	Nylon Line	Levels	Chisels and Caulking Tools	Levers	Manipulators	Brushes	Inflatable Bags	Foam Guns	Pyro-Technic Charge	TV Camera	Work Gloves and Pads	Knife	Illumination Kit	Tool Kit Container	Squalus Washer	Probe	Hardlines
Cutting																																																				
● **Saving**	x	x																																												·		x	x			
● **Shearing**				·																																										x		x	x			
● **Burning**																											·																			x		x	·			
● **Pyrotechnics**																																												·		x		x	x			
Torquing					·	·	·	·		·	·	·																																		x		·	x			
Hammering													·	·																																x		·	x			
Drilling															·	·	·																													·		x	x			
Punching																		·	·																											·		·	x			
Stud Driving																																																				
● **Riveting**																																														·		·	x			
● **Fastening**																					·																									·		x	x			
Sealing																																																				
● **Crimping**																						·																										x	x			
● **Vacuumizing**																							·																									·	x			
Welding																								·	·	·	·														·					x		·	x			
Coring															·	·												·																				·	x			
Calking/Coating													·																									·								·		·	x			
Guiding/Positioning																													·					·						·						·		·	x			·
Connect/Disconnecting					·	·	·	·		·	·	·	·							·				·	·	·			·	·	·	·	·						·					x		·	·	·	x			
De-embedding																																																				
● **Raising**															·	·								·	·	·				·	·	·	·		·	·			·	·		·	·			·		·	x			
● **Dislodging**													·																		·							·		·				·		·	·	·	x	·	·	·
● **Excavating**																																														·					x	

Note: x = hand tools
· = hand and mechanical manipulator tools

Source: Reference 15.

10. Covertness

A free swimming man has the advantage in covertness because of his small size and the availability of equipment to minimize visual, acoustic, magnetic, and electrical sensors. The equipments associated with the tethered man make this system's covertness factor comparable to that of the entire range of vehicle-oriented systems.

C. The Unique Capabilities of the Unshielded Man

- The unshielded man or MAN-IN-THE-SEA is unique in that:
  - He is compact and agile, which allows him to reach job sites of limited access and in congested structures.
  - He possesses manipulative skills unavailable in underwater mechanical manipulators.
  - He possesses tactile senses that allow him to accomplish manipulative tasks in extremely turbid waters.
  - As a free swimmer, he is relatively covert to visual, acoustic, magnetic, and electrical sensors.
- The unshielded man has capabilities comparable to those of the vehicle-oriented systems in operating time and in cognitive skills for on-site assessment of tasks.
- The unshielded man is at a disadvantage when compared with the alternative systems in operating depth capability, mobility capability, load carrying capability, and resistance capability to hazards.

D. Task Allocation Matrices

The last step taken during the study in identifying MAN-IN-THE-SEA missions within the total navy undersea mission spectrum was to generate a set of task allocation matrices. These matrices, which are shown in Tables 16 through 32, identify the tasks associated with a single functional operation or a specific set of them. The tasks are then related to the performance criteria that indicate the unique capabilities of MAN-IN-THE-SEA concepts. Therefore, the task allocation matrices are the integrating element of the comparative analysis for identifying MAN-IN-THE-SEA missions.

Table 16

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

SURVEILLANCE - LANDING BEACH AREA
ENEMY HARBOR
INSHORE USW
USW ALL RANGES AND DEPTH

FUNCTIONAL PERFORMANCE REQUIREMENTS / GENERALIZED TASK SPECTRUM	CLASS I	CLASS II			CLASS III			CLASS IV																			COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER CHIP	SCRAPE WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY						■																					
• SPEED																											
• RANGE						X																					
LOAD CARRYING						■																					
• OBJECT SIZE						X																					
• OBJECT WEIGHT						X																					
MANEUVERABILITY																											MAN-IN THE SEA UNIQUE CAPABILITY
• ACCESS LIMIT																											
• DEGREES FREEDOM																											
MANIPULATION					■		■																				
• MINIMUM SKILL					X		X																				
• MODERATE SKILL																											MAN-IN-THE SEA UNIQUE CAPABILITY
• COMPLEX SKILL																											
SENSING		■	■																								
• VISUAL		X	X																								
• ACOUSTIC		X	X																								
• ELECTROMAGNETIC																											
• MAGNETIC		X	X																								
• ELECTRIC		X	X																								
• TACTILE																											MAN-IN-THE SEA UNIQUE CAPABILITY
COGNITION		■	■																								
• ON SCENE ASSESS.		X	X																								
HARDNESS	ENEMY COUNTERMEASURES																										
• MECHANICAL	• EXPLOSIVES																										
• RADIATION	• ACOUSTIC NOISE GENERATORS																										
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS	ENEMY COUNTERMEASURES																										MAN IN THE SEA UNIQUE CAPABILITY (FREE SWIMMER [illegible])
• VISUAL	• UNDERWATER TV, SWIMMERS																										
• ACOUSTIC	• ACTIVE AND PASSIVE SONAR																										
• ELECTROMAGNETIC																											
• MAGNETIC	• MAGNETIC ANOMALY DETECTORS																										
• ELECTRICAL	• ELECTRIC FIELD DETECTORS																										
• PRESSURE	• PRESSURE FIELD DETECTORS																										

Table 17

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

RECONNAISSANCE - BEACH AREA
ENEMY HARBOR
MINING ENVIRONMENT

GENERALIZED TASK SPECTRUM / FUNCTIONAL PERFORMANCE REQUIREMENTS	CLASS I	CLASS II			CLASS III			CLASS IV																				COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH/LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER/CHIP	SCRAPE/WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY																											
• SPEED																											
• RANGE	X					X																					
LOAD CARRYING																											
• OBJECT SIZE						X																					
• OBJECT WEIGHT						X																					
MANEUVERABILITY																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• ACCESS LIMIT																											
• DEGREES FREEDOM																											
MANIPULATION																											
• MINIMUM SKILL				X	X		X																				
• MODERATE SKILL																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL																											
SENSING																											
• VISUAL	X		X	X																							
• ACOUSTIC	X		X	X																							
• ELECTROMAGNETIC																											
• MAGNETIC	X		X	X																							
• ELECTRIC	X																										
• TACTILE			X	X																							MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION																											
• ON SCENE ASSESS.	X		X	X	X	X	X																				
HARDNESS	ENEMY COUNTERMEASURES																										
• MECHANICAL	• EXPLOSIVES																										
• RADIATION	• ACOUSTIC NOISE GENERATORS																										
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS	ENEMY COUNTERMEASURES																										MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER ONLY)
• VISUAL	• LW TELEVISION, SWIMMERS																										
• ACOUSTIC	• ACTIVE AND PASSIVE SONAR, ACOUSTIC INFLUENCE MINES																										
• ELECTROMAGNETIC																											
• MAGNETIC	• MAGNETIC ANOMALY DETECTOR, MAGNETIC INFLUENCE MINES																										
• ELECTRICAL	• ELECTRIC FIELD DETECTOR																										
• PRESSURE																											

Table 18

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

MINING - MINE HUNTING AND COUNTERMEASURES

	CLASS I	CLASS II			CLASS III			CLASS IV																		
GENERALIZED TASK SPECTRUM / FUNCTIONAL PERFORMANCE REQUIREMENTS								ATTACH						DETACH						APPLY			EXCAVATE				COMMENTS
	SEARCH, LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER, CHIP	SCRAPE, WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY																											
• SPEED																											
• RANGE	X																										
LOAD CARRYING																											
• OBJECT SIZE					X	X	X																				
• OBJECT WEIGHT					X	X	X																				
MANEUVERABILITY																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• ACCESS LIMIT																											
• DEGREES FREEDOM																											
MANIPULATION																											
• MINIMUM SKILL					X		X																				
• MODERATE SKILL																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL																											
SENSING																											
• VISUAL	X		X	X																							
• ACOUSTIC	X		X	X																							
• ELECTROMAGNETIC																											
• MAGNETIC	X		X	X																							
• ELECTRIC	X		X	X																							
• TACTILE			X	X																							MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION																											
• ON-SCENE ASSESS.	X		X	X																							
HARDNESS	MINE HAZARDS																										
• MECHANICAL	• EXPLOSIVES																										
• RADIATION																											
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS	MINE HAZARDS																										MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER ONLY)
• VISUAL																											
• ACOUSTIC	• ACOUSTIC INFLUENCE MINES																										
• ELECTROMAGNETIC																											
• MAGNETIC	• MAGNETIC INFLUENCE MINES																										
• ELECTRICAL	• ELECTRIC INFLUENCE MINES																										
• PRESSURE	• PRESSURE INFLUENCE MINES																										

Table 19

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

MINING - MINE PLANTS

GENERALIZED TASK SPECTRUM → / FUNCTIONAL PERFORMANCE REQUIREMENTS ↓	CLASS I: SEARCH/LOCATE	CLASS II: OBSERVE	CLASS II: SURVEY	CLASS II: MEASURE	CLASS III: PICKUP	CLASS III: TRANSPORT	CLASS III: PLACE	CLASS IV ATTACH: WELD	CLASS IV ATTACH: DRILL	CLASS IV ATTACH: BOLT	CLASS IV ATTACH: RIVET	CLASS IV ATTACH: CONNECT	CLASS IV ATTACH: CLAMP	CLASS IV DETACH: BURN	CLASS IV DETACH: PYROTECHNIC	CLASS IV DETACH: DRILL	CLASS IV DETACH: SAW	CLASS IV DETACH: HAMMER CHIP	CLASS IV DETACH: SCRAPE/WIPE	CLASS IV APPLY: HOSE	CLASS IV APPLY: COAT	CLASS IV APPLY: PAINT	CLASS IV EXCAVATE: CORE	CLASS IV EXCAVATE: DREDGE	CLASS IV EXCAVATE: TRENCH	CLASS IV EXCAVATE: TUNNEL	COMMENTS
MOBILITY	■					■																					
• SPEED																											
• RANGE	X					X																					
LOAD CARRYING						■																					
• OBJECT SIZE						X																					
• OBJECT WEIGHT						X																					
MANEUVERABILITY																											MAN-IN-THE SEA UNIQUE CAPABILITY
• ACCESS LIMIT																											
• DEGREES FREEDOM																											
MANIPULATION							■																				
• MINIMUM SKILL							X																				
• MODERATE SKILL																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL																											
SENSING	■																										
• VISUAL	X																										
• ACOUSTIC	X																										
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRIC																											
• TACTILE																											MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION	■						■																				
• ON-SCENE ASSESS.	X						X																				
HARDNESS	ENEMY COUNTERMEASURES																										
• MECHANICAL	• EXPLOSIVES																										
• RADIATION	• ACOUSTIC NOISE GENERATORS																										
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS	ENEMY COUNTERMEASURES																										MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER ONLY)
• VISUAL	• UW TELEVISION, SWIMMERS																										
• ACOUSTIC	• ACTIVE AND PASSIVE SONAR																										
• ELECTROMAGNETIC																											
• MAGNETIC	• MAGNETIC ANOMALY DETECTOR																										
• ELECTRICAL	• ELECTRIC FIELD DETECTOR																										
• PRESSURE	• PRESSURE FIELD DETECTOR																										

Table 20

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

MINING - DISARM MINE

GENERALIZED TASK SPECTRUM → / FUNCTIONAL PERFORMANCE REQUIREMENTS ↓	CLASS I	CLASS II			CLASS III			CLASS IV																			COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH/LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER/CHIP	SCRAPE/WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY																											
• SPEED																											
• RANGE																											
LOAD CARRYING																											
• OBJECT SIZE																											
• OBJECT WEIGHT																											
MANEUVERABILITY																											
• ACCESS LIMIT																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• DEGREES FREEDOM																											
MANIPULATION																											
• MINIMUM SKILL																											
• MODERATE SKILL																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL			X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
SENSING																											
• VISUAL			X	X				X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRIC																											
• TACTILE			X	X				X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION																											
• ON-SCENE ASSESS.			X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
HARDNESS	MINE HAZARDS																										
• MECHANICAL	• EXPLOSIVES																										
• RADIATION																											
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS	MINE HAZARDS																										
• VISUAL																											
• ACOUSTIC	• ACOUSTIC INFLUENCE MINES																										MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER ONLY)
• ELECTROMAGNETIC																											
• MAGNETIC	• MAGNETIC INFLUENCE MINES																										
• ELECTRICAL	• ELECTRIC INFLUENCE MINES																										
• PRESSURE	• PRESSURE INFLUENCE MINES																										

Table 21

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

MINING - INTERROGATE MINE FIELD

GENERALIZED TASK SPECTRUM → / FUNCTIONAL PERFORMANCE REQUIREMENTS ↓	CLASS I	CLASS II			CLASS III			CLASS IV																			COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH, LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER/CHIP	SCRAPE/WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY																											
• SPEED																											
• RANGE	X																										
LOAD CARRYING																											
• OBJECT SIZE																											
• OBJECT WEIGHT																											
MANEUVERABILITY																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• ACCESS LIMIT																											
• DEGREES FREEDOM																											
MANIPULATION																											
• MINIMUM SKILL																											
• MODERATE SKILL																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL																											
SENSING																											
• VISUAL	X	X	X																								
• ACOUSTIC	X	X	X																								
• ELECTROMAGNETIC																											
• MAGNETIC	X	X	X																								
• ELECTRIC	X	X	X																								
• TACTILE																											MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION																											
• ON-SCENE ASSESS.	X	X	X																								
HARDNESS	MINE HAZARDS																										
• MECHANICAL	• EXPLOSIVES																										
• RADIATION																											
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS	MINE HAZARDS																										MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER ONLY)
• VISUAL																											
• ACOUSTIC	• ACOUSTIC INFLUENCE MINES																										
• ELECTROMAGNETIC																											
• MAGNETIC	• MAGNETIC INFLUENCE MINES																										
• ELECTRICAL	• ELECTRIC INFLUENCE MINE																										
• PRESSURE	• PRESSURE INFLUENCE MINE																										

Table 22

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

NAVIGATION SURVEY

GENERALIZED TASK SPECTRUM → / FUNCTIONAL PERFORMANCE REQUIREMENTS ↓	CLASS I	CLASS II			CLASS III			CLASS IV																			COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH/LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER/CHIP	SCRAPE WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY	■																										
• SPEED																											
• RANGE	X																										
LOAD CARRYING						■																					
• OBJECT SIZE						X																					
• OBJECT WEIGHT						X																					
MANEUVERABILITY																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• ACCESS LIMIT																											
• DEGREES FREEDOM																											
MANIPULATION			■	■	■		■																				
• MINIMUM SKILL			X	X	X		X																				
• MODERATE SKILL																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL																											
SENSING	■		■	■																							
• VISUAL	X		X	X																							
• ACOUSTIC	X		X	X																							
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRIC																											
• TACTILE																											MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION	■		■	■																							
• ON SCENE ASSESS.	X		X	X																							
HARDNESS																											
• MECHANICAL																											
• RADIATION																											
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS																											MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER ONLY)
• VISUAL																											
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRICAL																											
• PRESSURE																											

Table 23

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

RECOVERY - SMALL OBJECTS
- TORPEDOES
- NUCLEAR WEAPONS
- SPACE HARDWARE

GENERALIZED TASK SPECTRUM → / FUNCTIONAL PERFORMANCE REQUIREMENTS ↓	CLASS I	CLASS II			CLASS III			CLASS IV																			COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER, CHIP	SCRAPE, WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY	■																										
• SPEED																											
• RANGE	X																										
LOAD CARRYING						■																					
• OBJECT SIZE						X																					
• OBJECT WEIGHT						X																					
MANEUVERABILITY																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• ACCESS LIMIT																											
• DEGREES FREEDOM																											
MANIPULATION					■																						
• MINIMUM SKILL					X																						
• MODERATE SKILL																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL																											
SENSING	■		■																								
• VISUAL	X		X																								
• ACOUSTIC	X		X																								
• ELECTROMAGNETIC																											
• MAGNETIC	X		X																								
• ELECTRIC	X		X																								
• TACTILE																											MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION	■		■																								
• ON SCENE ASSESS.	X		X																								
HARDNESS																											
• MECHANICAL																											
• RADIATION	• NUCLEAR RADIATION HAZARDS																										
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS																											MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER [illegible])
• VISUAL																											
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRICAL																											
• PRESSURE																											

Table 24

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

RECOVERY - LARGE OBJECT

GENERALIZED TASK SPECTRUM → / FUNCTIONAL PERFORMANCE REQUIREMENTS ↓	CLASS I	CLASS II			CLASS III			CLASS IV																			COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH/LOCATE	OBSERVE	SURVEY	MEASURE	PICK UP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER, CHIP	SCRAPE, WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY																											
• SPEED																											
• RANGE	X																										
LOAD CARRYING																											
• OBJECT SIZE						X																					
• OBJECT WEIGHT						X																					
MANEUVERABILITY																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• ACCESS LIMIT								X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
• DEGREES FREEDOM																											
MANIPULATION																											
• MINIMUM SKILL				X	X		X		X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	
• MODERATE SKILL								X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL								X						X	X												
SENSING																											
• VISUAL	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
• ACOUSTIC	X	X	X	X																							
• ELECTROMAGNETIC																											
• MAGNETIC	X	X	X	X																							
• ELECTRIC	X	X	X	X																							
• TACTILE								•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION																											
• ON SCENE ASSESS.	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
HARDNESS																											
• MECHANICAL																											
• RADIATION																											
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS																											MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER ONLY)
• VISUAL																											
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRICAL																											
• PRESSURE																											

Table 25

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

FACILITY INSTALLATION - SONAR ARRAY (ALIGN & REPAIR)
BOTTOM MOUNTED ULM
GENERAL CONSTRUCTION

GENERALIZED TASK SPECTRUM / FUNCTIONAL PERFORMANCE REQUIREMENTS	CLASS I	CLASS II			CLASS III			CLASS IV																			COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH/LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER/CHIP	SCRAPE/WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY																											
• SPEED																											
• RANGE																											
LOAD CARRYING																											
• OBJECT SIZE						X																					
• OBJECT WEIGHT						X																					
MANEUVERABILITY																											
• ACCESS LIMIT								X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	MAN-IN-THE-SEA UNIQUE CAPABILITY
• DEGREES FREEDOM																											
MANIPULATION																											
• MINIMUM SKILL			X	X	X		X		X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	
• MODERATE SKILL								X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL								X						X	X												
SENSING																											
• VISUAL			X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRIC																											
• TACTILE								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION																											
• ON-SCENE ASSESS.			X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
HARDNESS																											
• MECHANICAL																											
• RADIATION																											
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS																											
• VISUAL																											
• ACOUSTIC																											MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER ONLY)
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRICAL																											
• PRESSURE																											

Table 26

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

FACILITY INSTALLATIONS - NAVIGATION MARKERS
CABLE LAYING AND INSPECTION

GENERALIZED TASK SPECTRUM → / FUNCTIONAL PERFORMANCE REQUIREMENTS ↓	CLASS I	CLASS II			CLASS III			CLASS IV																			COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH/LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER/CHIP	SCRAPE/WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY						■																					
• SPEED																											
• RANGE						X																					
LOAD CARRYING						■																					
• OBJECT SIZE						X																					
• OBJECT WEIGHT						X																					
MANEUVERABILITY																											
• ACCESS LIMIT																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• DEGREES FREEDOM																											
MANIPULATION					■		■																	■	■		
• MINIMUM SKILL					X		X																	X	X		
• MODERATE SKILL																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL																											
SENSING			■	■																				■	■		
• VISUAL			X	X																				X	X		
• ACOUSTIC			X	X																							
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRIC																											
• TACTILE																											MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION			■	■	■		■																	■	■		
• ON SCENE ASSESS.			X	X	X		X																	X	X		
HARDNESS																											
• MECHANICAL																											
• RADIATION																											
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS																											
• VISUAL																											MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER [illegible])
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRICAL																											
• PRESSURE																											

Table 27

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

FACILITY INSTALLATIONS - FOUNDATION AND BOTTOM
TUNNELLING
DAM BUILDING
WELL DRILLING

GENERALIZED TASK SPECTRUM / FUNCTIONAL PERFORMANCE REQUIREMENTS	CLASS I	CLASS II			CLASS III			CLASS IV																			COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH/LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER/CHIP	SCRAPE/WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY																											
• SPEED																											
• RANGE																											
LOAD CARRYING																											
• OBJECT SIZE																											
• OBJECT WEIGHT																											
MANEUVERABILITY																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• ACCESS LIMIT																											
• DEGREES FREEDOM																											
MANIPULATION																											
• MINIMUM SKILL																				X	X	X	X	X	X	X	
• MODERATE SKILL																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL																											
SENSING																											
• VISUAL																				X	X	X	X	X	X	X	
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRIC																											
• TACTILE																											MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION																											
• ON-SCENE ASSESS.																				X	X	X	X	X	X	X	
HARDNESS																											
• MECHANICAL																											
• RADIATION																											
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS																											MAN IN THE SEA UNIQUE CAPABILITY (FREE SWIMMER ONLY)
• VISUAL																											
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRICAL																											
• PRESSURE																											

Table 28

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

SALVAGE - SHIPS
AIRCRAFT

FUNCTIONAL PERFORMANCE REQUIREMENTS / GENERALIZED TASK SPECTRUM	CLASS I	CLASS II			CLASS III			CLASS IV																			COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH/LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER CHIP	SCRAPE, WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY																											
• SPEED																											
• RANGE	X																										
LOAD CARRYING																											
• OBJECT SIZE						X																					
• OBJECT WEIGHT						X																					
MANEUVERABILITY																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• ACCESS LIMIT								X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
• DEGREES FREEDOM																											
MANIPULATION																											
• MINIMUM SKILL				X	X		X		X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	
• MODERATE SKILL								X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL								X						X	X												
SENSING																											
• VISUAL	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
• ACOUSTIC	X	X	X	X																							
• ELECTROMAGNETIC																											
• MAGNETIC	X	X	X	X																							
• ELECTRIC																											
• TACTILE								•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION																											
• ON SCENE ASSESS.	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
HARDNESS																											
• MECHANICAL																											
• RADIATION																											
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS																											MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMING ONLY)
• VISUAL																											
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRICAL																											
• PRESSURE																											

Table 29

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

REPAIRS - IN PORT (WET DOCK)
UNDERWAY

GENERALIZED TASK SPECTRUM → / FUNCTIONAL PERFORMANCE REQUIREMENTS ↓	CLASS I	CLASS II			CLASS III			CLASS IV																			COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH/LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER/CHIP	SCRAPE/WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY																											
• SPEED																											
• RANGE																											
LOAD CARRYING																											
• OBJECT SIZE																											
• OBJECT WEIGHT																											
MANEUVERABILITY																											
• ACCESS LIMIT								X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					MAN-IN-THE-SEA UNIQUE CAPABILITY
• DEGREES FREEDOM																											
MANIPULATION																											
• MINIMUM SKILL									X	X	X	X	X			X	X	X	X	X	X	X					
• MODERATE SKILL								X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL								X						X	X												
SENSING																											
• VISUAL								X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRIC																											
• TACTILE								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●					MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION																											
• ON-SCENE ASSESS.								X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					
HARDNESS																											
• MECHANICAL																											
• RADIATION																											
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS																											MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER ONLY)
• VISUAL																											
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRICAL																											
• PRESSURE																											

Table 30

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

SUPPORT - OCEANOGRAPHIC DATA

GENERALIZED TASK SPECTRUM → / FUNCTIONAL PERFORMANCE REQUIREMENTS ↓	CLASS I	CLASS II			CLASS III			CLASS IV																				COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE					
	SEARCH/LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER-CHIP	SCRAPE/WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY						■																					
• SPEED																											
• RANGE						X																					
LOAD CARRYING						■																					
• OBJECT SIZE						X																					
• OBJECT WEIGHT						X																					
MANEUVERABILITY																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• ACCESS LIMIT																											
• DEGREES FREEDOM																											
MANIPULATION				■	■		■					■	■					■	■				■	■	■	■	
• MINIMUM SKILL				X	X		X					X	X					X	X				X	X	X	X	
• MODERATE SKILL				X																							MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL																											
SENSING		■	■	■																							
• VISUAL		X	X	X																							
• ACOUSTIC		X	X	X																							
• ELECTROMAGNETIC		X	X	X																							
• MAGNETIC		X	X	X																							
• ELECTRIC		X	X	X																							
• TACTILE		●	●	●																							MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION		■	■	■								■	■					■	■				■	■	■	■	
• ON SCENE ASSESS.		X	X	X								X	X					X	X				X	X	X	X	
HARDNESS																											
• MECHANICAL																											
• RADIATION																											
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS																											MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER ONLY)
• VISUAL																											
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRICAL																											
• PRESSURE																											

Table 31

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

SUPPORT - SUBMARINE RESCUE PERSONNEL

GENERALIZED TASK SPECTRUM → / FUNCTIONAL PERFORMANCE REQUIREMENTS ↓	CLASS I	CLASS II			CLASS III			CLASS IV																			COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH/LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER/CHIP	SCRAPE/WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY	■																										
• SPEED	X																										
• RANGE	X																										
LOAD CARRYING						■																					
• OBJECT SIZE						X																					
• OBJECT WEIGHT						X																					
MANEUVERABILITY								■	■	■	■	■	■	■	■	■	■	■	■								MAN-IN-THE-SEA UNIQUE CAPABILITY
• ACCESS LIMIT								X	X	X	X	X	X	X	X	X	X	X	X								
• DEGREES FREEDOM																											
MANIPULATION					■		■	■	■	■	■	■	■	■	■	■	■	■	■								
• MINIMUM SKILL					X		X		X	X	X	X	X			X	X	X	X								
• MODERATE SKILL								X	X	X	X	X	X	X	X	X	X	X	X								MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL								X						X	X												
SENSING	■	■	■																								
• VISUAL	X	X	X																								
• ACOUSTIC	X	X	X																								
• ELECTROMAGNETIC																											
• MAGNETIC	X	X	X																								
• ELECTRIC	X	X	X																								
• TACTILE																											MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION	■	■	■				■	■	■	■	■	■	■	■	■	■	■	■	■								
• ON SCENE ASSESS.	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X								
HARDNESS																											
• MECHANICAL																											
• RADIATION																											
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS																											MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER ONLY)
• VISUAL																											
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRICAL																											
• PRESSURE																											

Table 32

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:

SUPPORT - UNDERWATER LOGISTICS

GENERALIZED TASK SPECTRUM / FUNCTIONAL PERFORMANCE REQUIREMENTS	CLASS I	CLASS II			CLASS III			CLASS IV																			COMMENTS
								ATTACH						DETACH						APPLY			EXCAVATE				
	SEARCH/LOCATE	OBSERVE	SURVEY	MEASURE	PICKUP	TRANSPORT	PLACE	WELD	DRILL	BOLT	RIVET	CONNECT	CLAMP	BURN	PYROTECHNIC	DRILL	SAW	HAMMER CHIP	SCRAPE, WIPE	HOSE	COAT	PAINT	CORE	DREDGE	TRENCH	TUNNEL	
MOBILITY																											
• SPEED																											
• RANGE						X																					
LOAD CARRYING																											
• OBJECT SIZE						X																					
• OBJECT WEIGHT						X																					
MANEUVERABILITY																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• ACCESS LIMIT																											
• DEGREES FREEDOM																											
MANIPULATION																											
• MINIMUM SKILL					X		X					X	X					X	X	X	X						
• MODERATE SKILL																											MAN-IN-THE-SEA UNIQUE CAPABILITY
• COMPLEX SKILL																											
SENSING																											
• VISUAL	X																										
• ACOUSTIC	X																										
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRIC																											
• TACTILE																											MAN-IN-THE-SEA UNIQUE CAPABILITY
COGNITION																											
• ON SCENE ASSESS.		X										X	X					X	X	X	X						
HARDNESS																											
• MECHANICAL																											
• RADIATION																											
• TEMPERATURE																											
• MARINE LIFE																											
COVERTNESS																											MAN-IN-THE-SEA UNIQUE CAPABILITY (FREE SWIMMER ONLY)
• VISUAL																											
• ACOUSTIC																											
• ELECTROMAGNETIC																											
• MAGNETIC																											
• ELECTRICAL																											
• PRESSURE																											

E. MAN-IN-THE-SEA Missions

The Navy undersea missions that have associated essential tasks requiring the unique capabilities of the unshielded man are defined in Tables 33 through 35. These MAN-IN-THE-SEA missions, which were selected because of their undersea functional operations, are stated for two influencing conditions. The first considers system mission survivability, which is influenced by the criteria of covertness and hardness. Covertness implies that detection of the undersea mission would be minimized, which would result in reduced chances of enemy countermeasures. On the other hand, system survivability might be enhanced by hardening; however, this approach in general, would compromise covertness. Although the tradeoff between covert operation and hardened systems to improve mission survivability was not a task in this study, the effects of such tradeoffs on on mission allocation are indicated by identifying MAN-IN-THE-SEA missions with emphasis on covertness (Table 33) and with emphasis on hardness (Table 34).

In many areas of undersea activities, systems are designed specifically for undersea operations. The critical question here is: should a system be designed to optimize the use of vehicle-oriented systems or should it be optimized for MAN-IN-THE-SEA concepts? This question can only be answered after a thorough assessment of the costs of the alternatives--for example, the cost of constructing an undersea system to optimize the use of mechanical manipulators. The effects on mission allocation, if an undersea system is designed to optimize the use of hard systems, are shown in Table 35.

Table 33

DEFINITION OF MAN-IN-THE-SEA MISSIONS--SURVIVABILITY EMPHASIS ON COVERTNESS

UNDERSEA FUNCTIONAL OPERATIONS / ALTERNATIVE	MAN-IN-THE-SEA CONCEPTS: FREE SWIMMER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: DIRECT SURFACE TETHER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: INDIRECT SURFACE TETHER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: HABITAT TETHER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: VEHICLE TETHER	ALTERNATIVES TO MAN-IN-THE-SEA: MANNED FREE VEHICLE	ALTERNATIVES TO MAN-IN-THE-SEA: TETHERED VEHICLE: MANNED TETHERED VEHICLE	ALTERNATIVES TO MAN-IN-THE-SEA: TETHERED VEHICLE: UNMANNED TETHERED VEHICLE	ALTERNATIVES TO MAN-IN-THE-SEA: FIXED BOTTOM STATION
SURVEILLANCE	X					X			X
• LANDING BEACH AREA	X								
• ENEMY HARBOR	X								
• U.S. HARBOR PROTECTION						X			X
• INSHORE USW	X								
• USW ALL RANGES AND DEPTH						X			X
RECONNAISSANCE	X								
• BEACH AREA	X								
• ENEMY HARBOR	X								
• MINING ENVIRONMENT	X								
MINING	X	X	X	X	X	X			
• MINE HUNTING AND COUNTERMEASURE	X								
• MINE PLANTS						X			
• DISARM MINE	X	X	X	X	X				
• INTERROGATE MINE FIELDS	X								
NAVIGATION SURVEYS						X			
RECOVERY	X	X	X	X	X	X	X	X	
• SMALL OBJECT						X	X	X	
TORPEDOES						X	X	X	
NUCLEAR WEAPON						X	X	X	
SPACE HARDWARE						X	X	X	
• LARGE OBJECT	X	X	X	X	X	X	X		
FACILITY INSTALLATIONS	X	X	X	X	X	X	X		
• SONAR ARRAY (ALIGN AND REPAIR)	X	X	X	X	X	X	X		
• BOTTOM MOUNTED ULM	X	X	X	X	X	X	X		
• NAVIGATION MARKERS						X	X		
• CABLE LAYING AND INSPECTION						X	X		
• GENERAL CONSTRUCTION	X	X	X	X	X	X	X		
• FOUNDATION AND BOTTOM						X	X		
• TUNNELING						X	X		
• DAM BUILDING						X	X		
• WELL DRILLING						X	X		
SALVAGE	X	X	X	X	X	X	X		
• SHIP	X	X	X	X	X	X	X		
• AIRCRAFT	X	X	X	X	X	X	X		
REPAIRS	X	X	X	X	X	X	X		
• IN PORT (WET DOCK)	X	X	X	X	X	X	X		
• UNDERWAY	X	X	X	X	X	X	X		
SUPPORT	X	X	X	X	X	X	X	X	X
• OCEANOGRAPHIC DATA						X	X	X	X
• SUB RESCUE PERSONNEL	X	X	X	X	X				
• UNDERWATER LOGISTICS	X			X	X				
HABITAT DEVELOPMENT	X	X	X	X	X	X	X		X

Table 34

DEFINITION OF MAN-IN-THE-SEA MISSIONS--SURVIVABILITY EMPHASIS OF HARDNESS

ALTERNATIVE	MAN-IN-THE-SEA CONCEPTS: FREE SWIMMER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: DIRECT SURFACE TETHER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: INDIRECT SURFACE TETHER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: HABITAT TETHER	MAN-IN-THE-SEA CONCEPTS: TETHERED MAN: VEHICLE TETHER	ALTERNATIVES TO MAN-IN-THE-SEA: MANNED FREE VEHICLE	ALTERNATIVES TO MAN-IN-THE-SEA: TETHERED VEHICLE: MANNED TETHERED VEHICLE	ALTERNATIVES TO MAN-IN-THE-SEA: TETHERED VEHICLE: UNMANNED TETHERED VEHICLE	ALTERNATIVES TO MAN-IN-THE-SEA: FIXED BOTTOM STATION
UNDERSEA FUNCTIONAL OPERATIONS									
SURVEILLANCE						■			■
• LANDING BEACH AREA						■			■
• ENEMY HARBOR						■			■
• U.S. HARBOR PROTECTION						■			■
• INSHORE USW									■
• USW ALL RANGES AND DEPTH									■
RECONNAISSANCE									
• BEACH AREA									
• ENEMY HARBOR									
• MINING ENVIRONMENT						■			
MINING	■	■	■	■	■	■			
• MINE HUNTING AND COUNTERMEASURE						■			
• MINE PLANTS						■			
• DISARM MINE	■	■	■	■	■				
• INTERROGATE MINE FIELDS						■			
NAVIGATION SURVEYS						■			
RECOVERY	■	■	■	■	■	■	■	■	
• SMALL OBJECTS						■	■	■	
TORPEDOES						■	■	■	
NUCLEAR WEAPON						■	■	■	
SPACE HARDWARE						■	■	■	
• LARGE OBJECT	■	■	■	■	■	■	■		
FACILITY INSTALLATIONS	■	■	■	■	■	■	■		
• SONAR ARRAY (ALIGN AND REPAIR)	■	■	■	■	■	■	■		
• BOTTOM MOUNTED UIM	■	■	■	■	■	■	■		
• NAVIGATION MARKERS						■	■		
• CABLE LAYING AND INSPECTION						■	■		
• GENERAL CONSTRUCTION	■	■	■	■	■	■	■		
• FOUNDATION AND BOTTOM						■	■		
• TUNNELING						■	■		
• DAM BUILDING						■	■		
• WELL DRILLING						■	■		
SALVAGE	■	■	■	■	■	■	■		
• SHIP	■	■	■	■	■	■	■		
• AIRCRAFT	■	■	■	■	■	■	■		
REPAIRS	■	■	■	■	■	■	■		
• IN PORT (WET DOCK)	■	■	■	■	■	■	■		
• UNDERWAY	■	■	■	■	■	■	■		
SUPPORT	■	■	■	■	■	■	■	■	■
• OCEANOGRAPHIC DATA						■	■	■	■
• SUB RESCUE PERSONNEL	■	■	■	■	■				
• UNDERWATER LOGISTICS	■			■	■				
HABITAT DEVELOPMENT	■	■	■	■	■	■	■		■

Table 35

DEFINITION OF MAN-IN-THE-SEA MISSIONS--SURVIVABILITY EMPHASIS ON HARDNESS AND FACILITY DESIGN EMPHASIS ON OPTIMIZING THE USE OF HARD SYSTEMS

ALTERNATIVE			UNDERSEA FUNCTIONAL OPERATIONS																																									
			SURVEILLANCE	• LANDING BEACH AREA	• ENEMY HARBOR	• U.S. HARBOR PROTECTION	• INSHORE USW	• USW ALL RANGES AND DEPTH	RECONNAISSANCE	• BEACH AREA	• ENEMY HARBOR	• MINING ENVIRONMENT	MINING	• MINE HUNTING AND COUNTERMEASURE	• MINE PLANTS	• DISARM MINE	• INTERROGATE MINE FIELDS	NAVIGATION SURVEYS	RECOVERY	• SMALL OBJECT	TORPEDOES	NUCLEAR WEAPON	SPACE HARDWARE	• LARGE OBJECT	...ILITY INSTALLATIONS	• SONAR ARRAY (ALIGN AND REPAIR)	• BOTTOM MOUNTED UIM	• NAVIGATION MARKERS	• CABLE LAYING AND INSPECTION	• GENERAL CONSTRUCTION	• FOUNDATION AND BOTTOM	• TUNNELING	• DAM BUILDING	• WELL DRILLING	SALVAGE	• SHIP	• AIRCRAFT	REPAIRS	• IN PORT (WET DOCK)	• UNDERWAY	SUPPORT	• OCEANOGRAPHIC DATA	• SUB RESCUE PERSONNEL	• UNDERWATER LOGISTICS	HABITAT DEVELOPMENT
MAN-IN-THE-SEA CONCEPTS	FREE SWIMMER																																												
	TETHERED MAN	DIRECT SURFACE TETHER																																											
		INDIRECT SURFACE TETHER																																											
		HABITAT TETHER																																											
		VEHICLE TETHER																																											
ALTERNATIVES TO MAN-IN-THE-SEA	MANNED FREE VEHICLE																																												
	TETHERED VEHICLE	MANNED TETHERED VEHICLE																																											
		UNMANNED TETHERED VEHICLE																																											
	FIXED BOTTOM STATION																																												

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Appendix A

REVIEW OF MAN-IN-THE-SEA CONCEPTS

Appendix A

REVIEW OF MAN-IN-THE-SEA CONCEPTS

A. Basic Philosophy of MAN-IN-THE-SEA Concepts

MAN-IN-THE-SEA concepts are defined broadly in this study as any undersea system that requires exposing man to the ambient ocean pressure. MAN-IN-THE-SEA concepts are therefore those techniques associated with the well-known diving technologies. Diving technology has progressed from the hard hat diving techniques through the SCUBA (self contained underwater breathing apparatus) techniques, and finally to the prolonged undersea living experiments such as SEALAB, CONSHELF, and MAN-IN-THE-SEA.

Man's progress toward reaching greater diving depths and duration is a result of overcoming both physiological and technological problems. Until the 19th century, diving depth limits were imposed by such technological constraints as diving helmets, diving bells, and air compressor design. As the technological problems were solved, divers went deeper and remained longer, and the physiological problem of decompression was encountered. Decompression sickness or "the bends," one of the hazards of diving, was diagnosed in the 1870s. Under pressure, the inert gas in a breathing mixture (nitrogen in air) diffuses into the blood and other tissues. If the pressure is relieved too quickly, as in a rapid ascent from working depth, bubbles form in the tissues much as they do in a bottle of carbonated water when it is opened. Sudden decompression from a long deep dive can be fatal; even a slight miscalculation of decompression requirements can cause serious injury to the joints or the central nervous system. A diver must therefore be decompressed slowly, according to a careful schedule. Slow decompression enables diffusion of the inert gas from tissues to the blood and from the blood out to the lungs. Whereas decompression sickness was diagnosed and a cure (slow decompression) was developed, other physiological problems were encountered. These problems are nitrogen narcosis (inert gas toxicity) and oxygen poisoning (oxygen toxicity).

In an effort to solve the nitrogen narcosis problem, the Navy and the Bureau of Mines in 1924 began to conduct joint experiments with breathing mixtures consisting of inert helium gas and oxygen. By 1927, the work had progressed to the point where human subjects could be used. In 1937, using a helium-oxygen gas mixture, two Navy divers reached a simulated depth of 500 feet in one of the tanks at the Navy Experimental Diving Unit.

These dry land experiments were put to operational use in May of 1939 when the U.S. submarine SQUALUS sank in 243 feet of water. The helium-oxygen diving technique was used in 640 dives to the submarine without deaths or serious injury. On the basis of data obtained during the SQUALUS dives, the U.S. Navy established 380 feet as the new limit for operational diving with time limit of 30 minutes on bottom.

Up to that time, the hard hat technique was used--that is, man was tethered to a surface air compressor or gas supply. This tether drastically constrained the mobility of the diver. In the 1940s, the technological development commonly known as SCUBA or self contained underwater breathing apparatus allowed new freedom for man working in the underwater environment. Divorced of the need for the constraining umbilical to the surface, man was able to move about in the ocean with relative freedom. However, with the SCUBA technique, his depth-time capability is still limited by the amount of gas he is able to carry on his back.

The principal limitation in depth and duration of dives up to the late 1950s was still the requirement for decompression. The limit for U.S. Navy operational dives was 380 feet for 30 minutes on the bottom. Without complications, a dive of this depth and duration requires more than three hours of decompression--an unfavorable ratio of working time to decompression time of 1 to 6. This unfavorable ratio of work-to-decompression time was solved by the development of the "saturated diving" technique. Saturated diving technique capitalizes on the fact that at a given depth the amount of inert gas dissolvable into the body tissue is limited. After about 24 hours at a given depth the tissues become essentially saturated with inert gas at a pressure equivalent to the depth; they do not take up significantly more gas no matter how long the diver stays at that level. For example, a diver saturated to 300 feet requires the same decompression time (approximately 2-1/2 days) whether he spends one day or one month on the bottom. Therefore, if a diver must descend to a certain depth to accomplish a time-consuming underwater task, it is far more efficient for him to stay there than to return to the surface repeatedly, spending hours in decompression each time.

The U.S. Navy's MAN-IN-THE-SEA Program is based on the development of the saturated diving technique. The first experiments in the field of saturation diving were begun by the U.S. Navy in 1957 under the direction of Captain George Bond, using first a standard decompression chamber and then the climate-altitude chamber installed at the Naval Medical Research Laboratory in New London, Connecticut. These experiments were given the code name Genesis I, and the first phases were concerned with the reaction of animals under long term exposure to pressure and synthetic gas mixes. Late in 1962, three men were exposed to a helium-oxygen

breathing mixture at sea level pressure for six days. There were no observable physiological or psychological changes in the subjects.

In the next phase of Genesis I, conducted early in 1963, three Navy men lived for seven days in a two-section pressure chamber at the Experimental Diving Unit. The pressure in the chambers was similar to that encountered at a depth of 100 feet. The final phase of Genesis I was conducted at the Naval Medical Research Laboratory Test Chamber, with three men spending 12 days at a simulated ocean depth of 200 feet, again breathing a helium-oxygen gas mixture. The Genesis I experiments were completely successful and provided the physiological base for subsequent SEALAB experiments.

Since Captain George Bond's original proposal for the saturated diving technique, both the American inventor, Edwin Link, and the French oceanographer, Jacques-Yves Cousteau, have conducted significant work to advance saturated diving techniques. Their experiments were designated "MAN-IN-SEA" and "CONSHELF," respectively.

In the summer of 1964, the U.S. Navy conducted its first in situ experiment, designated SEALAB I, near the Oceanographic Research Tower, Augus Island, off Bermuda. Men lived in a 40-foot long chamber at a depth of 193 feet for 11 days. An extensive program of physiological studies was successfully pursued.

In the fall of 1965, the U.S. Navy conducted the SEALAB II experiment at La Jolla, California. Three 10-man teams remained at a depth of 205 feet for 15 days each. One man remained at that depth for the full 45 days of the experiment. In addition to living underwater and conducting a multitude of physiological experiments, underwater work tasks in simulated salvage, oceanography, and construction were performed. In all, the three teams achieved more than 300 man-hours of work outside the habitat.

SEALAB III, the most ambitious saturated diving experiment to date, probably will be conducted during the spring of 1969 at the Navy undersea range off San Clemente Island, California. In the SEALAB III experiment, five teams of eight men each will live successively in the sea floor habitat for 12-day periods. The habitat will be placed at a depth of 605 feet.

A summary of saturated diving or prolonged undersea living experiments conducted in the U.S. Navy MAN-IN-THE-SEA Program is shown in Figure 20. Civilian experiments by Edwin Link, Jacques-Yves Cousteau, and the Westinghouse Marine Contractor consortium are also summarized in the figure.

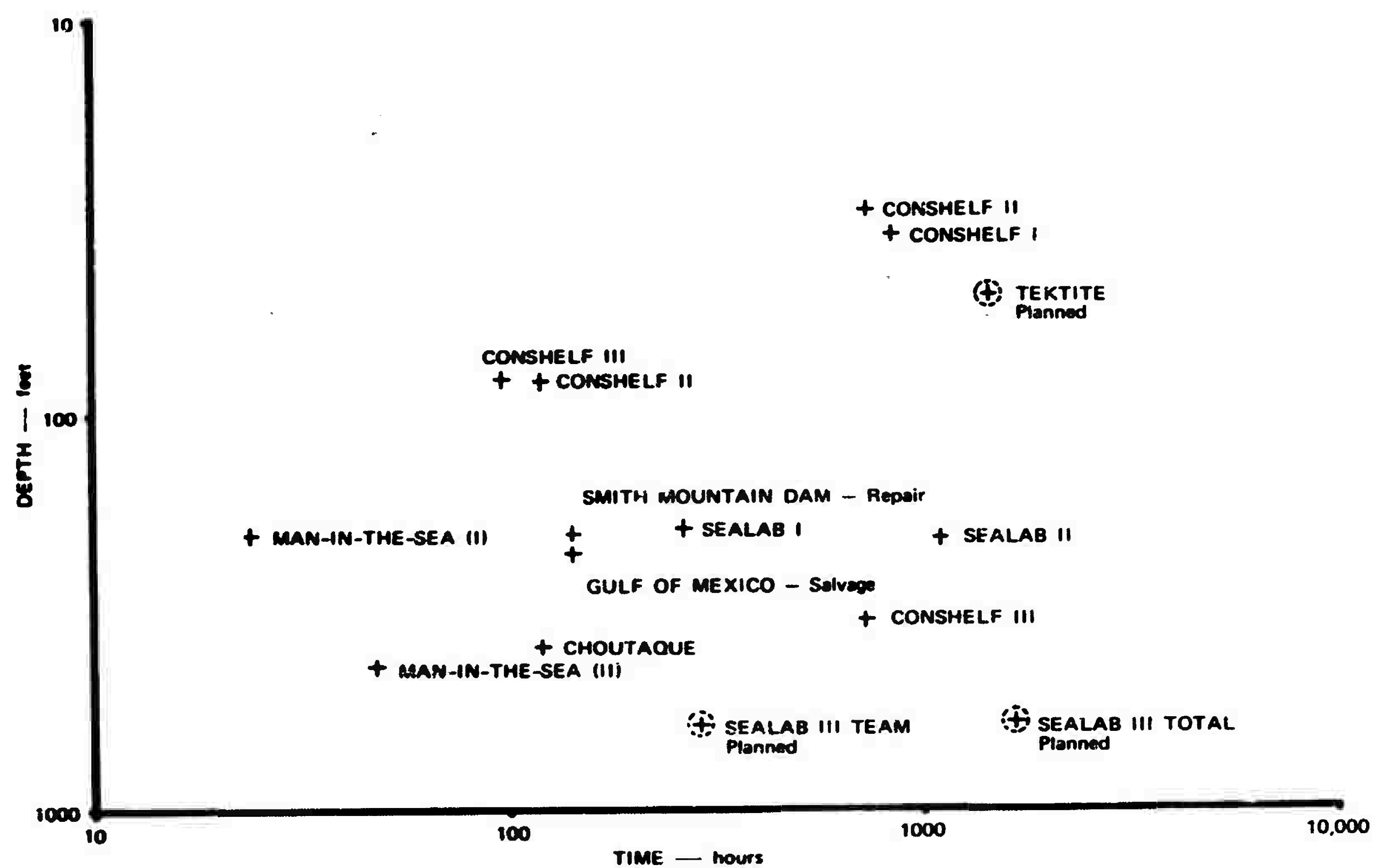


Figure 20 COMPLETED AND PLANNED PROLONGED SUBMERGENCE EXPERIMENTS TIME – HOURS 1,000

B. Current Status of MAN-IN-THE-SEA Concepts

The clearly defined needs of the U.S. Navy for salvage and submarine rescue, and the commercial needs of off-shore oil recovery operations and salvage operation, gave impetus to the transformation of the saturation diving technique from experimental to operational systems. Except in isolated cases, fully saturated long term undersea habitation and work have not been fully exploited. The principal reason has been that such operations have not been required. Notable exceptions have been the repair of the Smith Mountain Dam and the offshore oil rig salvage operation in the Gulf of Mexico. These operations, which were conducted by the Westinghouse-Marine Contractor consortium, are not true undersea habitation operations since the men were delivered to the work site at about 200 feet by a transfer capsule pressurized to the working pressure. After the work period, the men returned to the surface in the transfer capsule and there entered a chamber that is also pressurized to the pressure at the working depth. In this system, the men live in the ambient pressure environment for up to a week, alternating between work site and rest cycle in the surface chamber.

The development of the surface decompression chamber in combination with the personnel transfer capsule capitalized on the capabilities of saturation diving. At present, there are a large number of operational systems with depth capabilities varying from a minimum of 500 feet to a maximum of a 1,000 feet. Most of these operational saturation diving systems are in support of the offshore oil operations. Although one diving system differs from another in configuration and dimension, the basic system concepts are similar. In support of the U.S. Navy salvage and submarine rescue requirement, a diving system of the sort described is being constructed. This system called the Deep Dive System (DDS) Mark I is similar in concept to all other diving systems in operation. The following paragraphs describe the major components, the characteristics, and the operational sequence of the DDS MK I.

1. Mark I Deep Dive System

The MK I DDS comprises (1) two deck decompression chambers (DDC), (2) an entrance lock, (3) a personnel transfer capsule, (4) life support system, and (5) main control console as shown in Figure 21.

a. Deck Decompression Chamber. The Mark I System was developed for saturation diving, during which divers remain pressurized to their working depth for long periods and decompress only after completing multiple-dive objectives. The deck decompression chamber, which is shown

in Figure 22, provides a pressurized environment aboard the ship compatible with the saturated condition of the divers. The entrance lock, which is located between the deck decompression chambers, provides a pressure lock between the DDCs and the personnel transfer capsule, allowing transfer of divers while maintaining their pressure-saturated condition.

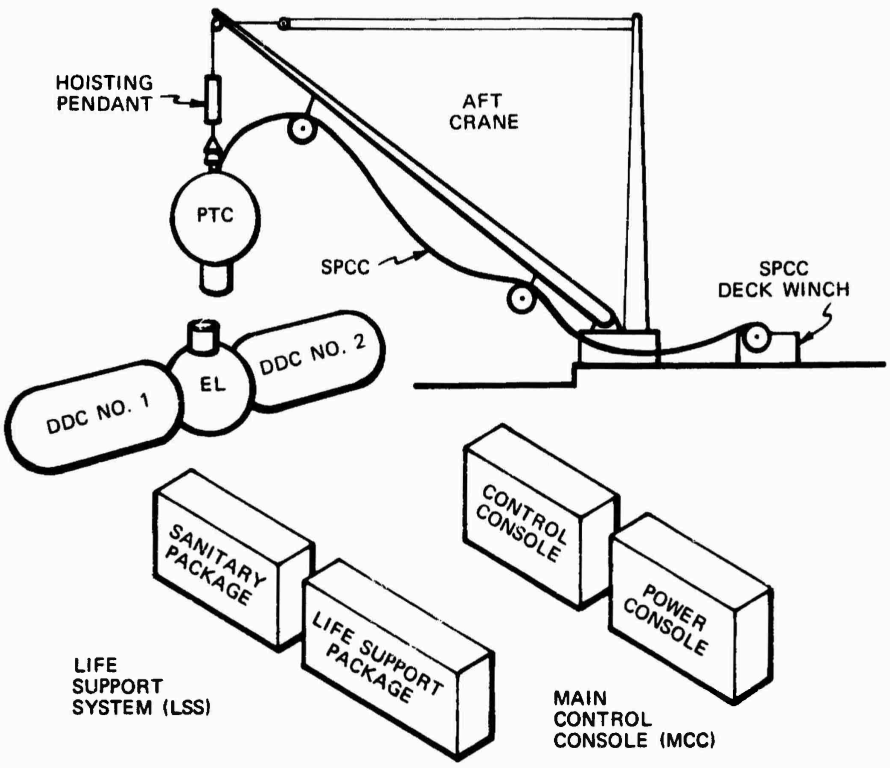


Figure 21 MARK I DEEP DIVE SYSTEM

The entrance lock has its own atmospheric system similar to that of the chambers (it can be used as a decompression chamber in an emergency). It permits access between the deck decompression chambers and either the deck of the ship or the personnel transfer capsule.

The Mark I DDS complex consists of two deck decompression chambers connected to an entrance lock. The entrance lock is spherical and has four flanged entry trunks with hatches as follows:

- Two trunks attach semipermanently to the deck decompression chambers.

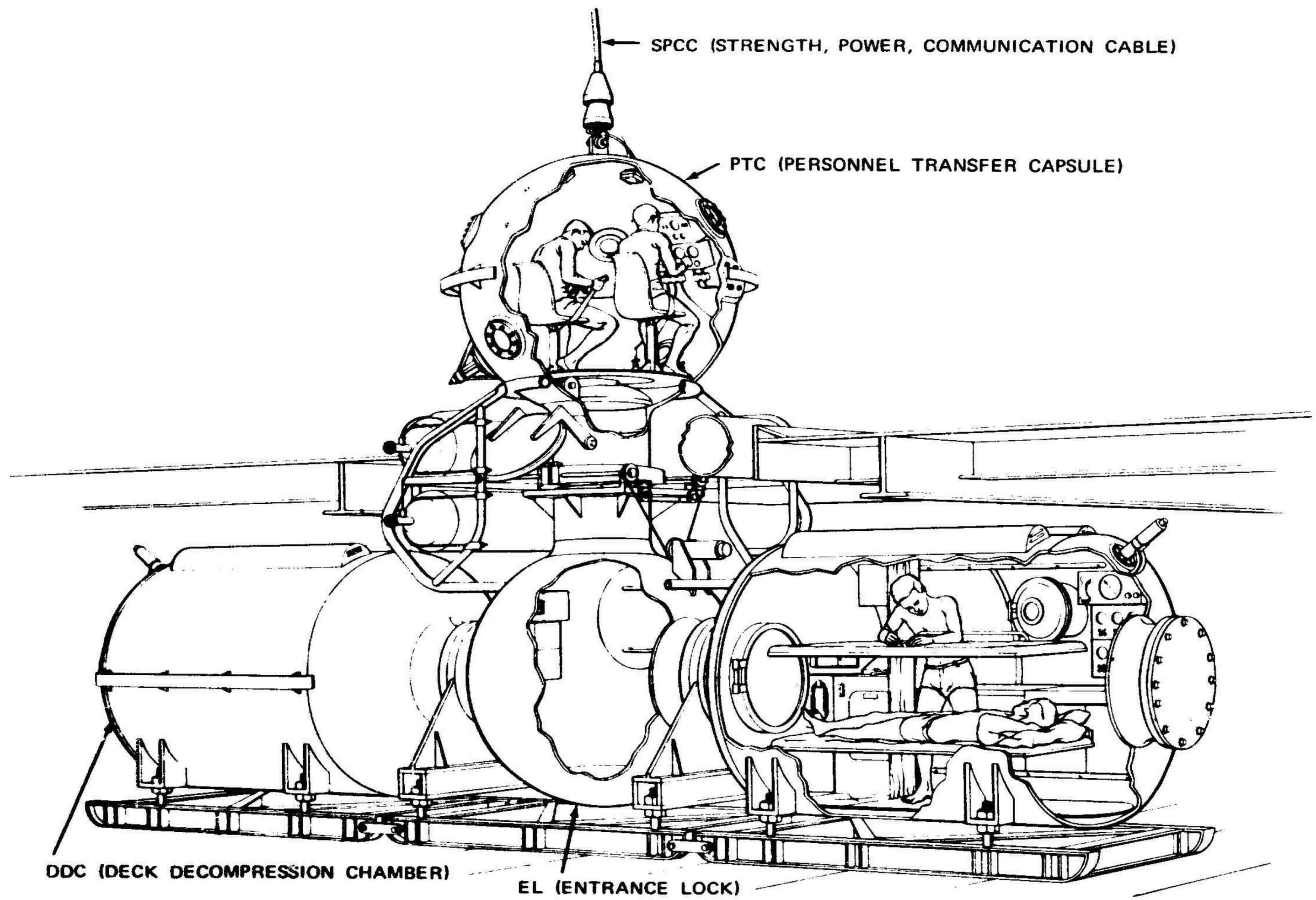


Figure 22 DECK DECOMPRESSION CHAMBER

- Another flange permits mating with the personnel transfer capsule in its normal vertical position.

- The fourth flange permits mating with the capsule in the horizontal position, which is required on some ships because of height limitations. This hatch also permits medical personnel to enter the complex as required.

b. Personnel Transfer Capsule. The personnel transfer capsule, the submersible of the Mark I DDS, serves the diving team as the transfer elevator to and from their underwater work site while maintaining the required pressurized environment. The configuration of the capsule is shown in Figure 23.

In its principal mode, the capsule is used to carry divers from the deck decompression chamber complex aboard the ship to the work site or the spot from which diver excursions will be made. In this mode, the capsule maintains the divers in an artificial atmosphere that has a gas pressure equal to the ambient seawater pressure at the divers' destination depth. When used on working dives, it can carry two or three divers at internal saturation pressures equivalent to 850-foot depths. At final equipment depth, a diver may leave the capsule through the lower lock and be sustained on "hookah" lines at distances up to 100 feet.

The capsule can also be used as a diving bell, with atmospheric air at surface-pressure of about 15 psia. In this mode, it is used only for observation, and, of course, the occupants remain inside the vessel. In the diving bell mode, the capsule can make sighting dives to depths of 1,000 feet.

2. Mark I Deep Dive System Operational Sequence

A typical sequence of operation during a saturation dive using the Mark I DDS is shown in Figure 24.

The surface tethered personnel transfer capsule with the working diver tethered to the capsule is constraint from the viewpoint of mobility. A development designed to increase the mobility of the diver is the free swimming deep submergence vehicles equipped with diver lockout/lockin capability. The deep submergence vehicle can be viewed as a mobile personnel transfer capsule. As visualized, the diver delivery vehicle will work in conjunction with the deck decompression chamber. Transfer from vehicle to the deck decompression chamber might be via a tethered personnel transfer capsule. This transition step would eliminate

HEIGHT-OVERALL	144 inches
DIAMETER	79" OD
MATERIAL OR CONSTRUCTION	HY80
CAPACITY	2 MEN
DURATION	30 hours
DEPTH	850 feet

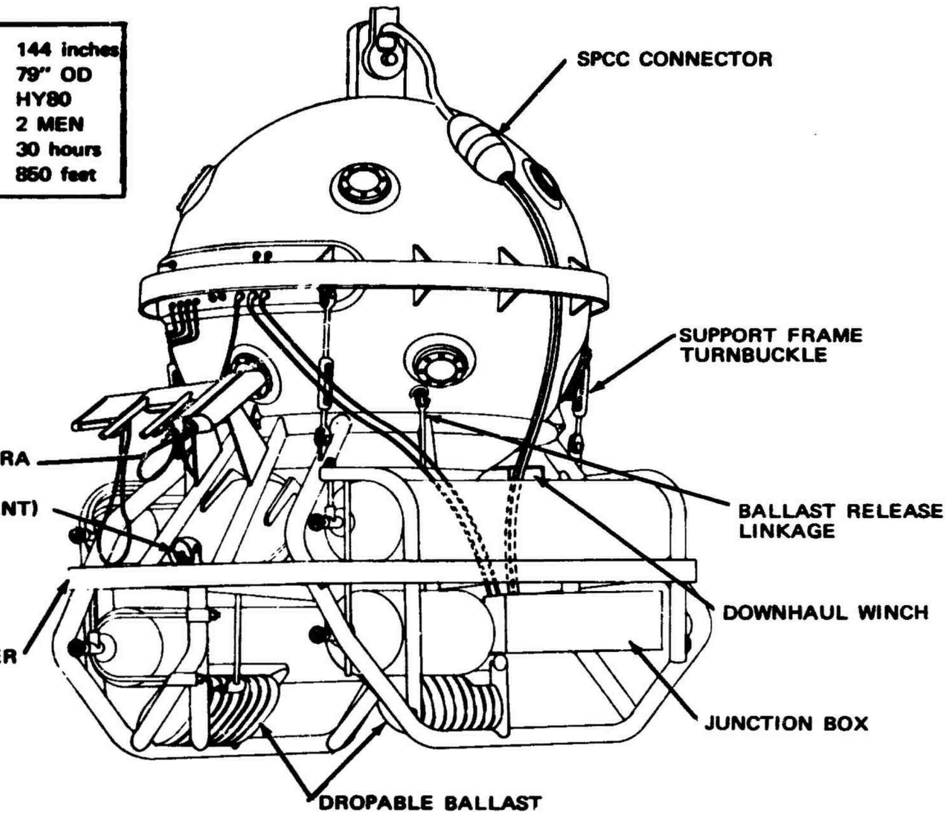


Figure 23 PERSONNEL TRANSFER CAPSULE

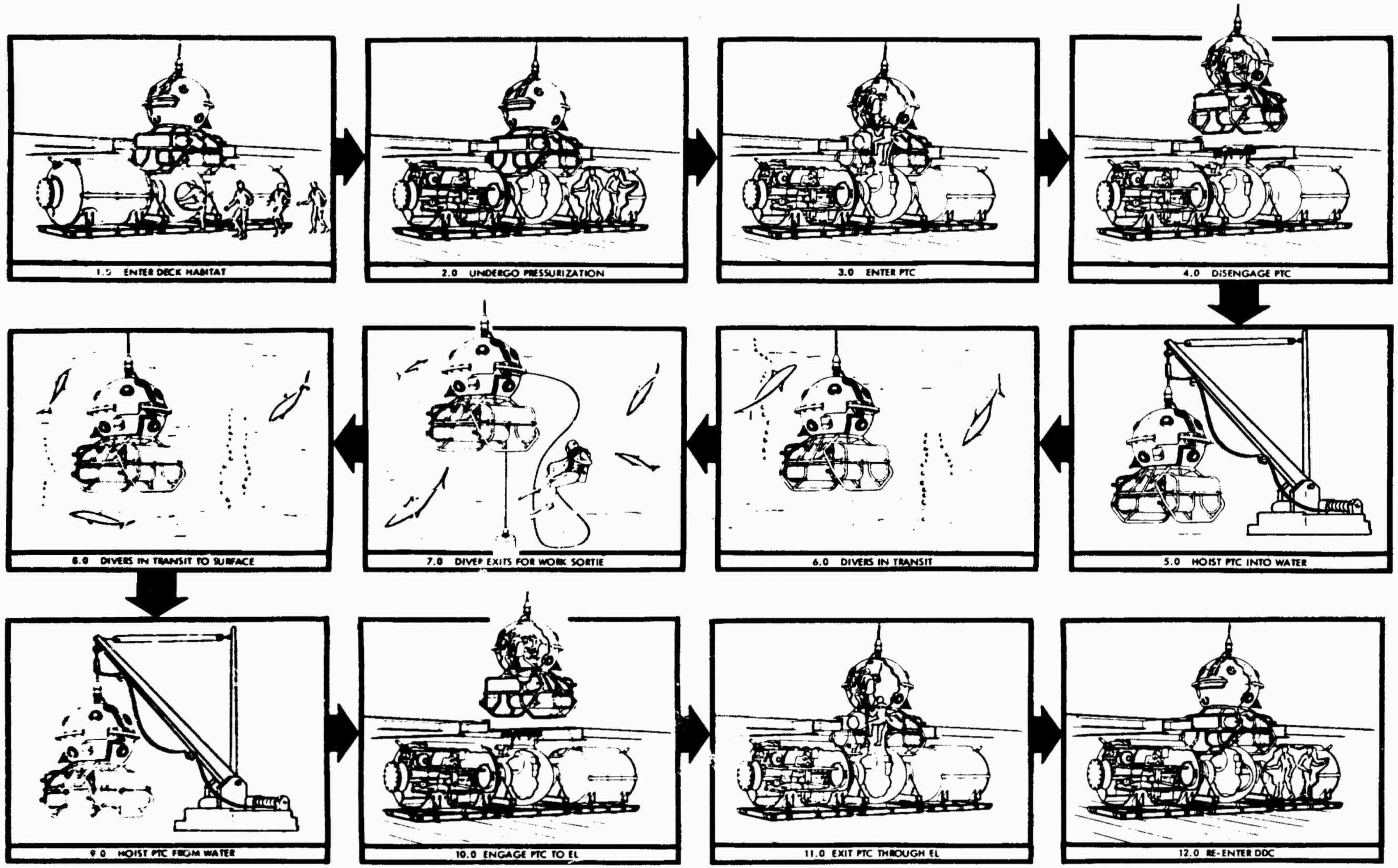


Figure 24 MARK I DEEP DIVE SYSTEM OPERATIONAL SEQUENCE DURING SATURATION DIVE

the need to lift and attach the deep submergence vehicle to the deck decompression chamber. Current operating vehicles with diver lockout capability are the Ocean Systems, Incorporated, Deep Diver vehicle, the North American Rockwell Beaver Mark IV vehicle, and the Lockheed Deep Quest vehicle. The Beaver Mark IV vehicle configuration is shown in Figure 25. The forward operator compartment is maintained at atmospheric pressure throughout an operation. The aft compartment and the diver transport compartment are maintained at atmospheric pressure during transit to the work site. If divers are needed to complete the job then the aft compartment is pressurized to ambient pressure. The diver then opens the bottom hatch and swims out to the job. The diver can either be free swimming or tethered to the vehicle. This choice depends primarily upon the job duration.

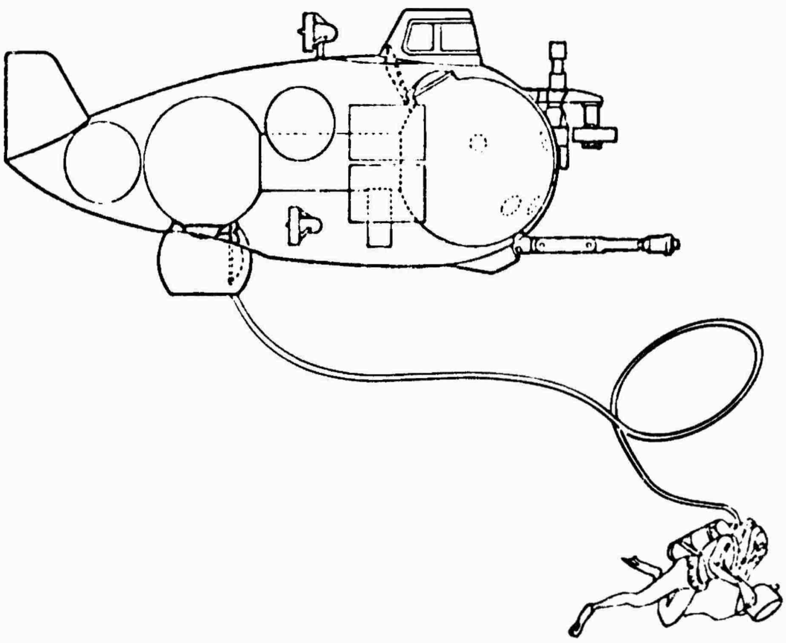


Figure 25 MOBILE PERSONNEL TRANSFER VEHICLE

Current MAN-IN-THE-SEA concepts can be divided into five classes in terms of the modes of operation: (1) the free swimming man equipped with SCUBA equipment; (2) the direct surface tethered man including the "hard hat" diver and the "hookah" diver; (3) the indirect surface tethered man as described for the Mark I Deep Dive System; (4) the fixed bottom site or habitat mode in which the diver is tethered to the habitat during excursions out of the habitat; and (5) the mobile vehicle tether, such as

that described for Beaver Mark IV. (The various modes of MAN-IN-THE-SEA concepts currently operational and contemplated are shown in Figure 9.)

A more advanced fixed bottom habitat approach has been suggested for the support of offshore oil recovery operations. One of the more recent ideas is one suggested by Ocean System, Incorporated. This concept for offshore oil drilling and production operation is illustrated in Figure 26. The basic element is a 40-foot diameter, buoyant, double-walled sphere, which is located between 100 feet and 150 feet. In a typical installation, a capsule would permit drilling and completion of nine producing wells, eight injection wells, and a spare well slot. The interior of the submerged sphere would be pressurized with mixed gas atmosphere to the ambient pressure environment. It would enable men to work in a shirt sleeve environment on a regular shift basis.

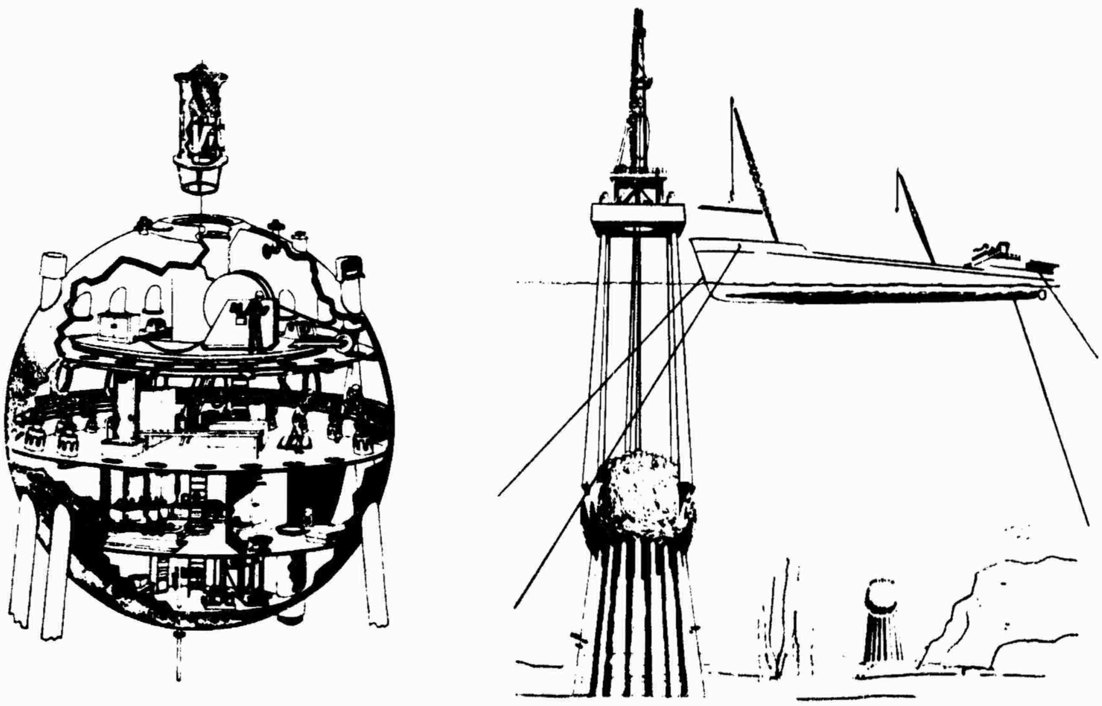


Figure 26 ADVANCE OFF-SHORE OIL RECOVERY SYSTEM EMPLOYING MAN-IN-THE-SEA CONCEPTS

C. The Focus of Underwater R&D Efforts

To satisfy the goals of prolonged habitation by man at ocean depths, ongoing research efforts are seeking a better understanding of the physiological and psychological problems related to exposing man to the ambient environment. Major R&D efforts are also being directed toward advancing

the technology associated with supporting the unshielded man. The psychological aspects of MAN-IN-THE-SEA research are focused toward understanding and measurement of diver performance impairment resulting from ambient environment exposure. MAN-IN-THE-SEA performance capabilities are reviewed in Appendix B in terms of (1) psychomotor performance, (2) mental task performance, (3) sensation and perception, and (4) communications. Current physiological research efforts are directed toward such problem areas as decompression, oxygen toxicity, inert gas toxicity, pulmonary ventilation, and hydrostatic force effects. Technological R&D efforts, which are closely integrated with physiological research, are concerned with breathing gas analysis, long duration breathing gas supply systems, heated diver dress, and diver functional support elements, including tools, communication and navigation equipment, and extended sensory aids. The following discussion examines the focus of R&D efforts associated with the physiological and technological aspects of MAN-IN-THE-SEA concepts.

1. Decompression

Decompression is the most familiar problem related to diving operations. This problem results directly from the increased solubility of gases with increased pressure. Exposure to high hydrostatic pressures during a dive causes components of the breathing gas to be taken up in solution by all body tissues. The rate of return to the surface is absolutely limited by the rate at which excess dissolved gases in the tissues can be eliminated. The rate of gas uptake or elimination is directly proportional to the diffusivity and gas partial-pressure gradient at the tissue-blood and lung-blood interface. Reliable decompression tables (safe ascent rate) for extended depth-time dives are being developed through improved computation methods and experimental validation. It is estimated by diving physiologists that, regardless of the inert gas used in a breathing mixture, the rate of ascent following prolonged submergence will never be increased much beyond the ten minutes per foot now achieved. This means that normal unaided decompression following a saturation dive to 500 feet will continue to require about three and one-half days. Inert gas elimination by unaided decompression will remain the primary factor limiting diving efficiency--i.e., useful diving time per unit of total time invested.

Several techniques are being examined that may provide practical aids to speed up decompression or to improve the safety of divers. These aids include: (1) the use of high oxygen tension, (2) the use of methods for extending oxygen tolerance, (3) the use of multiple gas mixtures, (4) the alternation of inert gases in the breathing mixture, (5) the combining of alternation of inert gases with fluctuation of oxygen tension,

and (6) the use of drugs to accelerate blood flow. A very advanced technique that cannot be classed as an aid to decompression is the concept of fluid breathing. This technique is an attempt to circumvent the whole problem of decompression by eliminating the need for inert gas. (This advanced diving concept is discussed in Section IV.) The following is a summary of the techniques being studied as aids to speeding up decompression.

a. High Oxygen Tension. The use of high oxygen tension is probably the first decompression aid discovered (1935) and will probably continue to be the most useful technique to speed up decompression. The technique calls for the use of high concentration of oxygen in the breathing mixture. The physiological principle exploited by this technique is to minimize the inert gas diffusion gradient (partial pressure difference) in the lung-blood and tissue-blood interface during descent and to maximize the diffusion gradient during ascent. The extent that the high oxygen tension technique can be used to aid decompression is limited by adequate definition of human oxygen tolerance. The problems encountered with oxygen at high pressures, i.e., oxygen toxicity, are discussed below.

b. Interrupted Exposure to High Oxygen Tension. A use of interrupted exposure to high oxygen tension is an attempt to circumvent the oxygen tolerance limits. It has been found that animals exposed intermittently to high oxygen tensions can tolerate longer total high oxygen tension exposure time. This approach is being used in a limited way to treat divers suffering from decompression sickness (bends).

c. Multiple Inert Gas. The use of multiple inert gas in breathing mixtures to aid decompression has been considered for several decades. The basic concept is clear, but results from actual trials are not conclusive. The fundamental assumption is that each gas in a gas mixture or dissolved in body fluids behaves as though it were the only gas present. The principle is that individual inert gas partial pressure will be decreased proportionately with increased number of inert gases used. Thus, the diffusion gradient for each gas is reduced. A hypothetical gas mixture offered in the First Symposium on Underwater Physiology uses nine gases, including oxygen, nitrogen, hydrogen, helium, neon, argon, krypton, xenon, and radon. The use at nine atmospheres of pressure with a nine gas mixture (equal volume) should not result in excess saturation of tissue fluids because each gas in the mixture is at a maximum partial pressure of one atmosphere. Nevertheless, severe decompression sickness does occur after exposure to multiple gas mixtures. The explanation for the effect is that once a cavity or a small bubble is formed, its growth depends upon the sum of the partial pressures of all gases in the tissue.

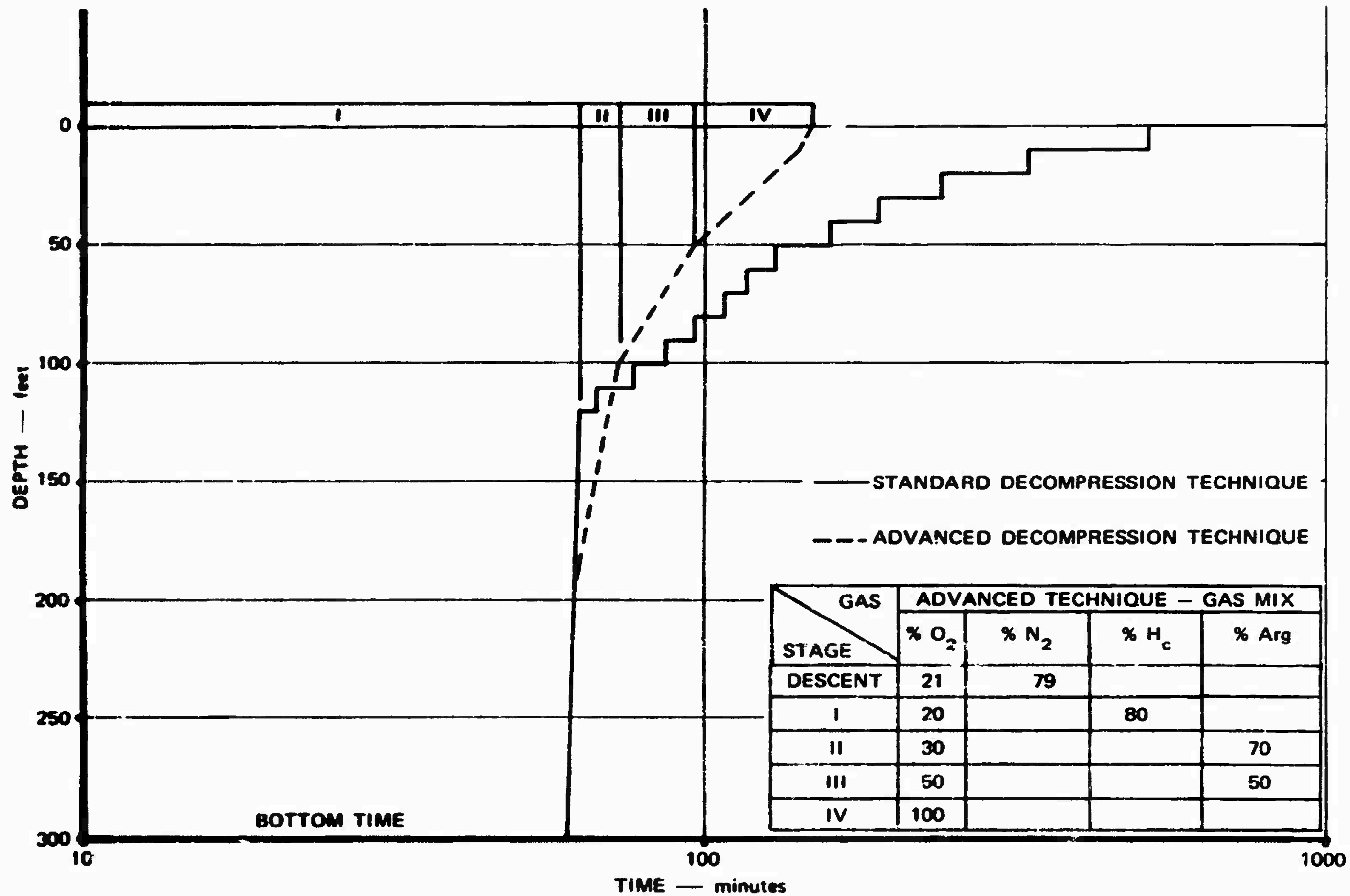
d. Alternation of Inert Gases and Fluctuation of High Oxygen Tension. A logical extension of the multiple gas breathing mixture technique and the high oxygen tension technique to speed up decompression is the combined use of both techniques. The use of alternation of inert gases in the breathing mixture combined with fluctuation of high oxygen tension continue to occupy the research efforts of diving physiologists. Figure 27 is a very simple example of the demonstrated capability of advanced decompression techniques versus that of the standard decompression technique. A total of 85 minutes is required for a 300 foot per 60-minute bottom time dive. This time compares with 455 minutes required by the standard air decompression table used by the U.S. Navy.

e. Drugs for Accelerating Blood Flow. The use of drugs has been suggested as a means of accelerating blood circulation in tissues during ascent to enhance the elimination of inert gases. The reverse effects--slowing up blood circulation during descent--would minimize inert gas take up. Although this technique is possible, no data are available to assess its possible contribution to the decompression problem.

2. Oxygen Toxicity

Pressure has a significant effect on the diver's oxygen requirements. Too much oxygen (hypeoxia) is almost as dangerous as too little oxygen (hypoxia). Short term exposure to high oxygen tension can affect the central nervous system causing localized muscular twitching and convulsions; long term exposure to high oxygen tension impairs the process of gas exchange in the alveoli, or air sacs, of the lung. The actual toxic effects of oxygen on the biochemical processes of the human body will probably not be known without many more years of research. A more precise definition of human tolerance to oxygen at high pressures must be known (1) to select the best oxygen level, which varies with the duration, depth, and phase of the dive, and the muscular effort required for a dive, and (2) to maximize the use of oxygen to speed up decompression.

Experience to date indicates that the partial pressure of oxygen should be kept between about 150 and 400 millimeters of mercury during the at-depth phase of a long saturation dive. The partial pressure of oxygen in the air we breathe at sea level is 160 millimeters of mercury (21 percent of 760). If oxygen is kept at 21 percent of the mixture, however, its partial pressure increases with depth--rising to 1,127 millimeters at 200 feet. As a result, the proportion of oxygen in the breathing mixture must be reduced as depth increases to maintain a partial pressure range of 150 to 400 millimeters of mercury. The band of tolerable oxygen percentage narrows rapidly with increased depth as shown in Figure 28. The need for increasing accuracy in the systems that analyze



GAS / STAGE	ADVANCED TECHNIQUE – GAS MIX			
	% O_2	% N_2	% H_c	% Arg
DESCENT	21	79		
I	20		80	
II	30			70
III	50			50
IV	100			

Figure 27 COMPARISON OF STANDARD AND ADVANCED DECOMPRESSION TECHNIQUES

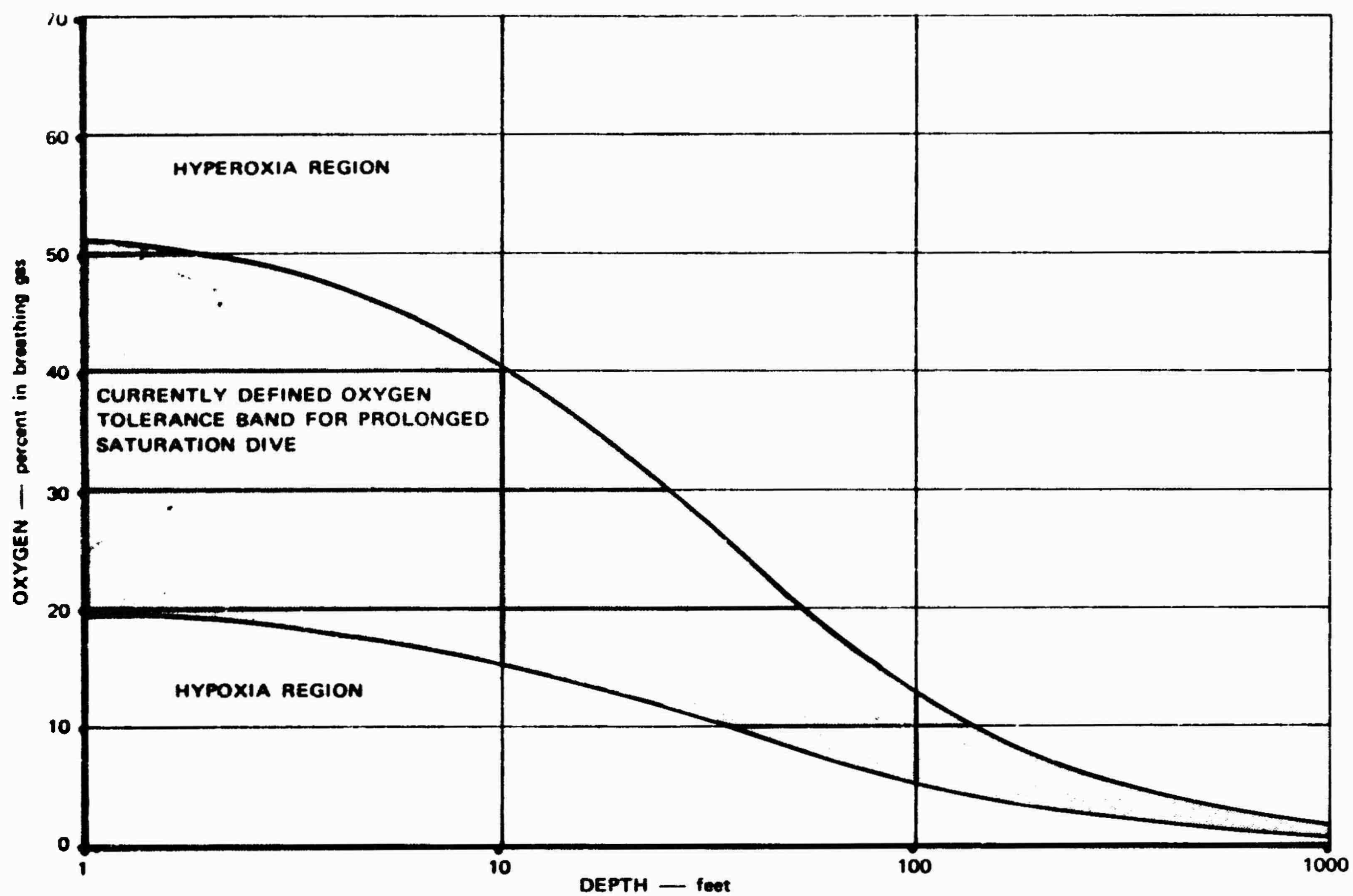


Figure 28 CURRENTLY DEFINED OXYGEN TOLERANCE BAND FOR PROLONGED SATURATION DIVE

and control breathing gas mixture for long term saturation dive is clearly indicated in the figure.

3. Inert Gas Toxicity

Gases, such as nitrogen and helium, that are biochemically inert in the atmospheric pressure environment are not so under increased pressure conditions. Nitrogen, which is physiologically inert at sea level, has an anesthetic effect under pressure. At depths greater than 100 feet, the average diver will suffer effects of nitrogen narcosis. The effects are impairment in judgment and psychomotor ability, which can render a diver completely unable to cope with emergencies. Helium has been found to be much less narcotic and is currently used instead of nitrogen in almost all deep-sea dives. Some experiments are also being conducted to determine the narcotic effects of hydrogen since there are indications that hydrogen has even less narcotic effect than helium. A set of curves published by Lambertsen indicate some depth limitations imposed by inert gas narcosis. These curves, which are shown in Figure 29, are not established through quantitative assessment of physiological or performance functions of man. The curves are approximations to indicate the general characteristics of inert gas narcosis. The curves indicate that serious impairment--loss of consciousness--occurs with less than 1 atmosphere of xenon and with less than 10 atmospheres (300 ft) of nitrogen, but more than 100 atmospheres (> 3300 feet) of pressure may be required to produce severe narcosis with helium. The prediction of helium narcosis limits is based on the observation that even at an inspired helium pressure of 120 atmospheres (4,000 feet), mice do not lose consciousness. Research efforts are currently being directed at (1) quantitatively defining performance impairment resulting from the narcotic effects of inert gases and (2) identifying the exact biochemical effects that result in inert gas narcosis.

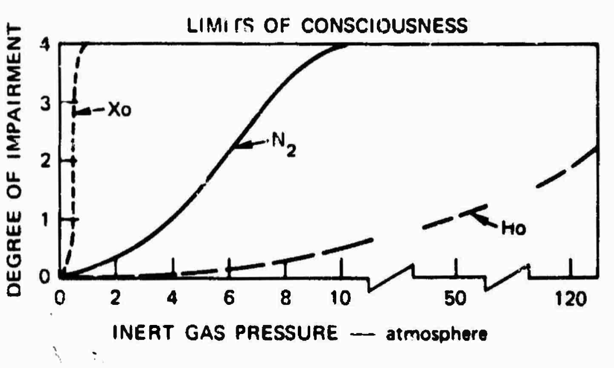


Figure 29 DEPTH LIMITS IMPOSED BY INERT GAS NARCOSIS

4. Gas Density and Viscosity

Elevation of pressure on any gas mixture increases its density and viscosity. The increased density and viscosity of breathing gas results in increased resistance to movement of gas through the small respiratory passages. This resistance not only interferes directly with pulmonary ventilation but also increases the work of breathing itself. The use of helium in the breathing gas mixture reduces gas narcosis effects and circumvents some of the breathing resistance problems. Since nitrogen is about seven times more dense than helium at one atmosphere, the density of nitrogen at about 200 feet of seawater is as great as that of helium at 1,000 feet. The major method for reducing respiratory resistance at very great depths will be the use of less dense and less viscous gases, such as helium or hydrogen. A technological solution to the respiratory resistance problem might be the development of a respiratory pump. This pump will provide the necessary assistance in the work of moving air in and out of the lungs.

5. Temperature

The human body can maintain its thermal equilibrium only within very narrow limits. Both high and low temperatures represent human physiological limitations. In water above normal body temperature, fever develops even at rest and exercise accelerates the onset of fever. In water below normal body temperature, the unprotected man will lose heat about 21 times faster than he would in normal air at the same ambient temperature. Metabolic heat porduced by exercise extends the tolerance to cold water, and the combination of insulation (wet suit) and work provides useful periods of time in water at temperatures down to 55-60^{o}F. Significant improvement in human temperature tolerance cannot be expected from the use of drugs or physiological adaptation. Rather, human temperature tolerance must be achieved by the use of insulating and external heating methods properly integrated with the understanding of physiological heat exchange.

6. Hydrostatic Pressure Effects (Pressure Syndrome)

If the problems of decompression, oxygen toxicity, inert gas toxicity, gas density and viscosity, and temperature can be circumvented through physiological research and technological improvements, the final barrier to man's attempt to go deeper into the sea is the direct effects of hydrostatic pressure. Whereas the effects of pressure on human cellular structure and the resultant body functional impairments are essentially unknown, experiments have been conducted with animals and animal tissues that indicate existence of direct pressure effects. A major difficulty

in studies of this type is the inability to isolate causes of observed effects. For example, deterioration of mental performance, which is ascribed to helium narcosis, might be only the onset of pressure effects on the nerve cell structure. Tremors, sweating, dizziness, and redness in the face, which might be ascribed to CO_2, could be direct effects of hydrostatic pressure.

In any case, it has been demonstrated in recent decades that hydrostatic pressure effects include: (1) failure of gel formation, (2) failure of cell division, (3) failure of ameboid movement, (4) inhibition of biological luminescence, and (5) inhibition of the growth of bacteria. Most of these effects appear to be related to the volume changes in cells. It is important to diving physiologists that bacterial growth is inhibited by pressures as low as 1,000 feet of sea water. This effect suggests the possibility that hydrostatic pressure has some influence at the depths where man still hopes to live for long periods. Recent simulated and operational deep ocean dives (greater than 600 feet) have indicated some pressure effects on bone-muscle structures. Divers working at depths exceeding 600 feet have shown an increasing tendency toward dislocated joints. Although the number of incidents cannot support firm conclusions, there appear to be some bone-muscle effects resulting from high hydrostatic pressures that must be investigated.

7. Technology

R&D efforts in diving technology can be separated into two categories. The first is associated with the life support aspects of technology--that is, the hardware or systems that are needed to maintain the physiologic environment that is essential to sustain life in the ambient ocean pressure. The second is associated with functional support of man--that is, the hardware or systems that aid man in accomplishing undersea tasks (e.g., diver tools, communication equipment, navigation equipment, sonar, television, and propulsion aids). The following discussion deals only with life support technology. The identification of the requirements for functional support technology is, in fact, the objective of the overall MAN-IN-THE-SEA program.

The focus of current R&D efforts in life support technology is in the following areas.

It was indicated in the description of the physiological problems of diving that increasing diving depth is placing more stringent requirements on the makeup of breathing gas mixture and monitoring of gas concentrations. The physiological effects of oxygen, inert gases, and contaminants are generally proportional to partial pressure rather than to percentage

concentration. Since the partial pressure is the product of concentration and total pressure, the allowable concentration of any substance becomes smaller as diving depth is increased. For example, at 100 feet, the range of oxygen percentage is 3.75% to 7.50% and carbon dioxide percentage is 0% to 0.50%. At 1,000 feet, the oxygen percentage is 0.48% to 0.97% and carbon dioxide percentage is 0% to 0.06%. Reliable devices for sensing, monitoring, and controlling the gas environment at high pressures must be developed. Moreover, methods of detecting and eliminating contaminants, such as carbon monoxide, must be developed. Unless atmospheric gases can be reliably controlled, full exploitation of the diving capabilities of man will not be possible.

Closely related to the development of reliable sensing, monitoring, and controlling devices for providing a safe breathing gas environment at high pressure is the continuing development of a reliable and safe closed-circuit, mixed gas, self-contained underwater breathing apparatus. Present day breathing devices are limited in depth-time capability because of the need to exhaust portions of the breathing gas during each breath. The open or semiclosed SCUBA devices do not fully exploit the full amount of gas a free swimming man can carry. The totally closed circuit oxygen rebreather is limited in depth because of the problems of oxygen toxicity. The following paragraphs describe briefly the current devices in the U.S. Navy inventory and in research and development.

a. Standard SCUBA. The demand or open-circuit SCUBA is a militarized version of the commercial device used by sports divers. The system is open circuit in that expired gases are discharged into the water during exhalation. Normal compressed air is the breathing gas medium; however, it is possible to use mixed gases for deep dives. Open-circuit systems are inherently wasteful of gases. About three-fourths of the oxygen in each breath drawn from the gas cylinder is discharged into the water. The principal component of the open-circuit SCUBA is the demand regulator which releases compressed gas to the diver during the inspiratory cycle. A pressure regulator maintains the breathing system at ambient depth pressure; the regulator opens to create a slight negative pressure at the start of inspiration and remains open until the end of inspiration.

b. Mark VI SCUBA. The Mark VI SCUBA is a semiclosed-circuit, mixed gas breathing device. The gas mixture can be oxygen-nitrogen or oxygen-helium, depending on the diving depths required. A volume of gas mixture flows from storage cylinders through a regulator into an inhalation breathing bag. Exhaled gas is then forced through a carbon dioxide removal canister and back into the inhalation bag. As oxygen is used up in the breathing volume (inhalation bag), a critical level is reached

whereupon a fresh volume of gas mixture is transmitted from the storage cylinder to the breathing bag. The waste gas is then exhausted into the sea. The recirculating breathing apparatus allows a maximum utilization of available oxygen, thereby increasing diving duration. However, the need to exhaust inert gases still limits the useful dive duration.

c. Closed-Circuit Oxygen SCUBA. The closed-circuit oxygen SCUBA, which is issued primarily to underwater demolition teams and SEALAB teams, employs a breathing device similar to the Mark VI. However, pure oxygen is used as the breathing medium rather than mixed gases. The device can be used only to depths less than 30 feet because of the oxygen toxicity problem. The primary purpose of such a device is to maximize covertness; no waste gas needs to be exhausted into the sea, thereby eliminating tell-tale bubbles.

d. Mark VIII SCUBA. The Mark VIII SCUBA is similar to the Mark VI SCUBA in that it is a semiclosed circuit device. The Mark VIII, which was developed specifically for the SEALAB III experiment, will use an oxygen-helium gas mixture. The gas can be supplied through hoses from the habitat or from diver-carried cylinders. In the tethered mode, a maximum duration of 3 hours at 600 feet can be achieved, using a single charge of baralyme in the carbon dioxide absorbent canister. In the free swimming mode, two 90-cubic-foot cylinders provide sufficient gas for 1 hour at 600 feet. The Mark VIII breathing system configuration for the SEALAB III experiment is shown in Figure 30.

All of the breathing apparatus described above is constrained in depth-time capability by the need for a premixed gas supply stored in swimmer carried cylinders or gas supplied through hoses. A closed-circuit device where breathing gas is mixed on-site is being developed to extend the depth-time capabilities of current breathing apparatus. The success of such a system will depend on the development of a compact, rugged, and reliable oxygen sensing and flow control device that can maintain oxygen content within the narrow safety boundaries. A closed-circuit mixed gas SCUBA is currently being developed for the Navy. The depth-time capability of SCUBA might be extended through the use of cryogenic gas storage concepts. While cryogenic storage and gas mixing techniques are being developed, no information is available at this time.

Development of heated diving suits will be essential to the achievement of extended diving operations. Open-circuit hot water suits have been used successfully in the past few years. This technique will be used to support the SEALAB III divers. A battery supplied resistance wire heat suit was tried during the SEALAB II experiments, but it is limited

by the available energy-density of the battery pack. A nuclear isotope hot water heater combined with the open-circuit hot water suit concept will be tried during the SEALAB III experiment. The base of the heated suit problem is in the development of a compact energy source, which is a technological area that is receiving major research attention for many application areas.

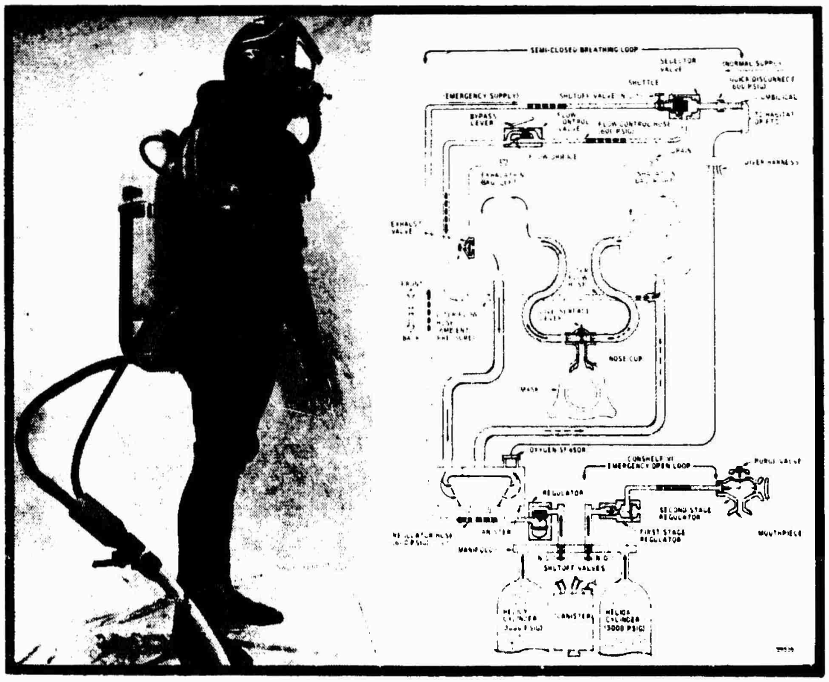


Figure 30 CONFIGURATION OF THE MARK VIII BREATHING APPARATUS

Ancillary equipments that are being developed to support divers include advanced head gear, depth gauge, and decompression computers. A "clamshell" helmet has been developed, which will be used by SEALAB III divers. It provides a full face mask with oral/nasal insert and complete head protection. Most important, the helmet provides the necessary air cavity for voice communications. The helmet is lightweight because it does not require a neck seal and its free-flooding feature around the back of the head reduces the requirement for weight compensation.

F. <u>Advanced MAN-IN-THE-SEA Concepts</u>

Advanced MAN-IN-THE-SEA concepts reflect two developments aimed at sending man to deeper ocean depths for longer duration. These developments

are the techniques of fluid breathing and the use of artificial gills for gas exchange. Experimental evidence indicating that the mammalian lung can function as gills was presented in 1962. It was found that adult mice, rats, and dogs can live for prolonged periods of time submerged with lungs filled with fluid--in salt solutions equilibrated with oxygen at high pressures. Under these conditions, the submerged mammals continued making respiratory movements, were apparently capable of extracting adequate amounts of dissolved oxygen from the aqueous environment. The animals were not killed by hydrostatic pressures of up to 160 atmospheres which is equivalent to a depth in the ocean of one mile.

The potential practical importance of this phenomenon is clear. The problem of decompression sickness would be circumvented since the inert "filler" gas would no longer be present. No inert gas would dissolve in the blood and tissues of a diver with fluid-fill lungs; consequently, he would be free to ascend to the surface at any time and as rapidly as he desired without fear of bubble formation. The problem of inert gas narcosis would also be avoided. If the fluid breathing concept proves to be physiologically feasible in all ways, the depth that man can reach as a diver would be limited only by the effects of hydrostatic pressure on cellular structure. However, the use of the fluid breathing technique by humans is still far in the future because the physiologic effects of fluids on the lung tissues are still not known. Furthermore, gas exchange in liquid-filled lungs is diffusion-limited, and at least 60 times more work is required to propel equal amounts of water instead of air through the lung passages. These factors seriously restrict carbon dioxide elimination in water-breathing mammals. In mechanically ventilated water-breathing dogs, carbon dioxide elimination was always deficient. The use of fluid breathing techniques by man will come about only through extensive research into the effects of fluids on lung tissue and through solution of the problem of carbon dioxide elimination.

Fish obtain oxygen for their metabolic demands by diffusion from the seawater in which they swim and eliminate carbon dioxide in the same way. Diffusion takes place in the gills of the fish where water and blood are in intimate contact, separated mainly by a series of cell membranes. The same physcial factors that operate to supply oxygen and eliminate carbon dioxide in fish gills--i.e., membranes with appropriate permeability properties--can be used in the design of artificial gills. An artificial gill, which could enable submerged men to obtain oxygen by diffusion from water, would have obvious advantages. Work on such gills has been carried out in several laboratories, and recently a U.S. patent was awarded to the designer of one. The problem of obtaining oxygen by diffusion from water is essentially one of developing a proper membrane. The membrane must permit passage of the oxygen molecules while restraining the water

molecules. There are membranes in existence that would satisfy the diffusion requirements.

The ultimate system that would allow man to roam the ocean freely for long periods of time might come about by the combined use of the fluid breathing technique with the extraction of oxygen from seawater by artificial gills. The development of such a system is very far in the future and can result only through extensive R&D efforts.

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Appendix B

REVIEW OF THE PERFORMANCE CAPABILITIES OF MAN-IN-THE-SEA CONCEPTS

Appendix B

REVIEW OF THE PERFORMANCE CAPABILITIES OF MAN-IN-THE-SEA CONCEPTS

A. Psychomotor Performance

1. Effects of Water Temperature

In general, it has been found that precision of fine-dexterity of manual performance deteriorate as water-temperature decreases.[1] It has been noted that the same task performed in SCUBA diving dress on dry land and in 70°F water shows a performance-time increase in water of 23%,[1] ascribed simply to the "various impediments . . . incurred" by being submerged. Subjects in the experiments cited performed all tasks bare-handed and did not wear gloves during any part of the experiment. Thus, their hands were continuously exposed to the ambient environment. It was further noted that as water-temperature decreases, performance decreases; the experimenters postulate " . . . a point somewhere between 54° and 60°F below which chilling of the hands produces a rapidly increasing crippling of performance." These results were obtained at a single, shallow depth (25 feet) in a tank, the divers breathing normal air supplied by self-contained underwater breathing apparatus. Thus, the possible effects of depth/pressure and gas-mixtures were not considered in these experiments. Bowen and Pepler's[1]* postulated critical temperature ". . . somewhere between 54° and 60°F . . ." is supported by the earlier findings of Clark,[2] in studying the effects of hand skin temperature (in air) upon knotting performance (requiring very fine finger dexterity), observed severe degradation at 55°F; he further noted that ". . . performance decrement at that temperature increased exponentially with exposure duration, becoming asymptotic after about 40 minutes. Contrastingly, performance at 60°F hand skin temperature remained uneffecting throughout the exposure period" (sic).

In the most definitive study of water-temperature effects on motor performance yet reported,[3] finger dexterity deteriorated much more markedly than did ability to carry out tasks requiring relatively large

* References appear at the end of each appendix.

movements of grosser muscle-groups, at the lowest of three temperatures (70°, 60°, and $50^\circ F$). Moreover, fine-dexterity performance tended to deteriorate earlier during the 1-1/2 hour immersion period; both types showed a tendency to reach an asymptotic level well before the end of the period. This conclusion elaborates and probably further supports Bowen and Pepler's critical-temperature assertion, as well as Clark's observation. Stang[3] further shows that performance of all tasks at the other two temperatures (70° and $60^\circ F$), remained relatively stable through time but were significantly affected by the actual difference between thermal levels. His subjects worked in a small-volume tank at 8-foot water depth, breathing normal air from SCUBA. No dry-land data were taken to show deterioration resulting from the water-immersion effect; practice on all experimental tasks was provided at $60^\circ F$.

2. Effects of Pressure and Water Immersion

To set a base-line for evaluating their subjects' underwater performance, Bowen and Pepler had them perform the same tasks on dry land that they performed in the experimental tank. While the ambient temperature of the dry-land environment is not reported, the authors note that to a diver in a wet suit (as their subjects were), $70^\circ F$ water feels warm. Thus, the significant decrease in performance found between dry-land and $70^\circ F$ immersion is attributed "simply to being in the water," which was 25 feet deep (equivalent in fresh water to 1.75 atmospheres or 25.8 psi). Hill[4] in studying the dry-land and underwater performance of engineer-diver teams working on "routine service jobs" replicating oil and gas production facility maintenance operations, found a highly significant deterioration of performance at 30-foot depth in a tank of $65^\circ F$ water. Tasks carried out apparently included various combinations of fine and gross dexterity and probably some total-body movement. Since no statement is made about diver equipment utilized, it is not possible to assess the encumbering effects of wet suits, SCUBA tanks, gloves, breathing gas, and the like. The author surmises that part of the difficulty experienced by his subjects in using hand tools, especially a hammer, rose from visual distortion (due to air-water mismatch at the divers' face masks) and "poor stability in a near weightless state."*

In a series of experiments designed to study manual force-production capabilities of SCUBA swimmers, Streimer, Turner, and Volkmer[5] found that the lack of traction resulting from the swimmers' state of neutral buoyancy caused a significant decrease in the force applied to the turning of

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* Assuming fresh water, the depth at which this experiment was carried out would exert pressure equivalent to 1.9 atmospheres, or [illegible].9 psf.

hand wheels of various diameters and in one- and two-handed pushing and pulling operations, when compared with forces exerted in "the normally tractive state" (sic; not otherwise described, but presumed to be on dry land). In another study,[6] the authors showed that work underwater was more time-consuming than the same tasks done on dry land, with a mean increase of 35%, which is statistically significant. They concluded that the type of work performed was differentially affected by immersion (12-18 feet, 62° - 64°F) times for upper-torso work increased 32%, for gross body "translations" 61%, and for work requiring relatively fine manual dexterity, 78% to 100%.

With regard to the specific effects of hyperbaric gas-pressures on performance (dry-land laboratory conditions), Kiessling and Maag[7] showed insignificant decrease in performance (modified Purdue Pegboard, requiring fine digital-manual manipulations) and that, after an initial decrease in effectiveness with increasing pressure, performance remains impaired but relatively constant, improving as pressure diminishes toward sea level. The experiments were performed in a pressure-chamber at atmospheric pressures simulating a 100-foot water depth. Results were attributed to the narcotic effect of elevated partial pressure of nitrogen in the atmosphere (normal air). Subsequently, Baddeley[8] compared the effects of simulated versus actual immersion depth-pressures, concluding that manual dexterity is much more seriously impaired by 100 feet of seawater than by atmospheric pressure simulating that depth; he warns that it is " . . . unwise to generalize from pressure chamber experiments to underwater performance." During SEALAB II, a number of strength and psychomotor tests were administered before and during immersion to individuals and to teams; results showed systematically increasing deterioration of performance from dry-land to shallow-depth to habitat-depth.[9]

To test the effects of depth further, Baddeley, de Figueredo, Curtis, and Williams[10] administered two fine-dexterity tests to divers in both open-sea and pressure-chamber environments, at depths of 5 and 100 feet, using compressed air as the breathing gas. Performances on both tests deteriorated slightly but significantly as depth was increased.

3. Effects of Gas Mixture

Baddeley and Flemming[11] compared manual dexterity of divers at 10-foot and 200-foot depths both in open sea and in a dry pressure-chamber and breathing compressed air and found that both air-breathing and HeO_2-breathing divers showed a significant decrease in effectiveness at

200 feet in the sea compared with their performance at 10 feet. Further, HeO_2 divers were significantly more accurate than air divers. In the dry-chamber part of the experiment, decrements that were concluded to stem from pressure alone were found for both types of breathing-gas. The authors sum up by noting that ". . . 10 percent impairment in manual dexterity in a pressure chamber becomes a 30 percent decrement in the open sea," the effect being independent to a considerable extent of both depth and gas mixture (except that air induces greater impairment than HeO_2).

4. Effects of the Nature of the Psychomotor Task

As previously noted, Stang[3] showed that fine dexterity performance is more sensitive to deteriorative effects of immersion than is performance of grosser character. Bowen & Pepler's data[1] analyzed for percentage performance decrements as a function of temperature at the long exposure values, tend to agree: a relatively gross manipulative test showed 11.25%, a finger dexterity test 19%, and a two-hand coordination test 100% decrement. The data of Streimer, Turner, and Volkmer[6] suggest further agreement, in that fine dexterity work suffered 78% to 100% degradation while gross-movement tasks deteriorated from 32% to 61%. However, their findings suggest that in gross movement work, those tasks that require the use of larger patterns of musculature may be subject to greater degradation than those requiring the use of smaller muscle-groups: time to complete work requiring use of the upper torso only increased (from dry-land times) 32%, while jobs requiring whole-body movements took 61% longer. Results from SEALAB II individual assembly tests tend to agree with the initial formulation and further suggest that the more complex a manipulative task may be, the more it may be impaired by underwater working conditions (Ref. 9, pp. 259-260).

B. Performance of Mental Tasks

1. Effects of Pressure, Gas Mixtures, and Immersion

At an atmospheric pressure simulating 100 feet of seawater, using compressed air, Kiessling and Maag[7] found that both choice reaction time and conceptual reasoning were significantly degraded compared with responses at sea level and attributed the result to nitrogen narcosis. They noted further that when their subjects had been decompressed to an equivalent depth of 10 feet allowing 100-foot compression, their performance returned to "approximatel· normal." Bennett, Poulton, Carpenter, and Catton[12] tested 80 subjects on a card-sorting task at sea level

and at 33-foot (2 ats abs) and 100-foot (4 ats abs) pressures, in compressed air and in 20% oxygen in helium. They reported significantly more errors at the 100-foot depth when subjects breathed air than when they breathed HeO_2; this effect was not found at the 33-foot depth. Moreover, subjects made significantly more errors when breathing air at 100 feet than at surface pressure. It was noted that all subjects worked faster and less accurately at 100-foot depth, regardless of breathing gas mixture, than they did at surface pressure. Authors attribute this to "an increase in the level of arousal at depth." Baddeley & Flemming[11] found that, at 200-foot depths in the open ocean, divers worked more slowly at an arithmetic addition task than they did at 10-foot depths, regardless of whether they were breathing compressed air or HeO_2, but that only when breathing air did they show a marked increase in error rate (at 200 feet). Replicating their procedure in a dry pressure tank, they found evidence to support the conclusion that at 200-foot depth the HeO_2 breathing diver works slightly faster and considerably more accurately than the air-breathing diver.

In another study,[10] Baddeley et al. found that a reasoning test using sentence comprehension showed about the same decrement between open-sea depths of 4 and 100 feet, and in a dry pressure chamber simulating the pressures at those depths, the breathing gas being compressed air. The depth effect was significant, but the change from open sea to pressure chamber was not. The authors explain the former on the basis of nitrogen narcosis, the latter on the subjects' lack of apprehension about conditions surrounding the open-sea diving phase.

During SEALAB II, arithmetic tests were given to the diver-subjects; however, they were administered <u>inside</u> the habitat, under 200-foot HeO_2 pressure saturation, rather than in the water under diving conditions.[13] The authors report a slight, probably not significant, improvement in performance compared with pre-SEALAB dry-land trials.

2. Effects of Temperature

Bowen and Pepler[1] had their subjects undertake two problem-solving tests and one memory test, at water temperatures of 72° and 47°F, as well as on dry land. In all cases, performance after long exposure at the lower temperature showed deterioration compared with similar exposure at the higher temperature, although the differences were not tested for significance. Stang[3] had his subjects perform a choice-reaction procedure while solving problems in addition as a loading task; his data clearly show the

deteriorative effects of diminishing water temperature: at 60°F reaction times were significantly longer than at 70°F, although at both temperatures they did not vary significantly throughout the 90 minutes. However, at 50°F there was sharp lengthening of reaction time for the first hour, followed by a leveling-off at about 1-1/2 times the reaction times obtained at 70°F. This asymptotic performance at 50°F persisted throughout the rest of the experimental period and represented a highly significant degradation compared with the 70°F reaction time.

3. Effects of Emotional State

From the available literature, it does not appear that controlled experiments have yet been performed relating the effects of induced emotional states such as task-induced stress in the form of anxiety. (See Hecker, Stevens, von Bismarck, and Williams,[14] for example.) However, several observers have reported behavior incidental to performance under water, which they ascribe to emotional components. Baddeley,[8] in discussing the problems of open-sea diver performance research, surmises that anxiety about personal safety, the reliability of life-support equipment, and the effect of nitrogen narcosis may interact with experimental variables to contaminate results. Baddeley et al.[10] in their later study of the effects of nitrogen narcosis again cite the probable complications resulting from emotional (i.e., anxiety) stresses associated with open-sea diving, re-emphasizing the point made earlier by Baddeley & Flemming[11] in their study of the performance of deep-submergence HeO_2 divers. In their assessment of SEALAB II divers' performance, Bowen, Andersen, and Promisel[13] summarize results of a self-administered checklist completed several times by each member of each team during his 15-day submergence. Certain of the items were designed to enable measurement of anxiety or apprehension experienced by the individual; this class of response, called "fear" by the experimenters, was found to be positively correlated to a significant degree with another attribute, labeled "arousal," signifying reactivity to the SEALAB conditions and manifested by high variability between hyperactivity and withdrawal (lassitude, unwillingness to make sorties from the habitat, and the like). Further, "fear" and "arousal" were found to be negatively correlated, at a highly significant level, with time spent on diving missions and with number of sorties made, suggesting that the most active individuals were those who felt least tense and anxious about the SEALAB situations. In their study of perceptual narrowing in novice divers, Weltman and Egstrom[15] reported that some of the subjects' reaction times to stimuli in the visual periphery were atypically prolonged and surmised that "their behavior appeared more closely related to diving risk than to other environmental factors." It is emphasized that the subjects in this experiment were, by the authors'

definition, inexperienced, i.e., students. This study is unique among the work reviewed in connection with this project, in that it attempted to assess the effects of emotional state on divers' performance under water. While the authors admit that their perceptual-narrowing hypothesis is only partially "validated" by their results, they append to their report a bibliography that should not be overlooked in future research of this nature.

C. Sensation and Perception

1. Auditory

Included in the sensory testing program of SEALAB II[9] were audiometric tests to determine effects of deep-submergence environments on threshold hearing acuity. Conclusions resulting from analysis of the data are that divers' hearing levels tend to resemble those of people exposed to high intensity noise and that very little change in threshold acuity occurs for frequencies in the speech-reception range (below 3,000 Hz), although there was a trend of hearing loss at the higher frequencies (above 3,000 Hz). (An experiment intended to assess underwater audibility of single-frequency tones at 500 and 5,000 Hz, and binaural localization of tone sources by divers at SEALAB II depth was not conducted, according to the authors, because of insufficiently powerful underwater sound transmission systems.)

Considerable laboratory work has been performed on the intelligibility of speech transmitted in compressed-air and HeO_2 environments, both over direct talker-listener paths and through electrical transmission systems. Divers' face-masks and breathing apparatus are known to affect their speech and therefore its reception by other divers and surface support personnel. Available reports indicate that the severest problems lie in the areas of speech production rather than auditory reception; they will be discussed under a specific Communications heading to follow. However, it is appropriate to note here that aquanauts participating in SEALAB II (Ref. 9, p. 266) reported that an apparent adaptation occurred during each 15-day cycle, in which the speaker seemed to become more intelligible as time went on; the divers attributed this to the lowering of voice pitch and a slowing-down of speaking rate. The authors state that word lists and phrases recorded during the 45-day submersion period (presumably intended to measure the effects of hyperbaric HeO_2 on speech) were to be carefully analyzed; however, no results of such analysis are reported in the SEALAB II document.

Auditory localization of underwater sound sources (such as homing devices or sources of potential hazard) is discussed in a report produced by CBS Laboratories in connection with describing an electronic device developed to augment human capability.[16] Although this discussion cites no specific experimental evidence or other publications, it argues that localization of sound sources by unaided underwater operators (swimmers, divers) is sharply limited compared with dry-land capability because of the increased propagation-velocity of sound in water, transmission properties of the human skull, and the effects of reverberation and multipath propagation prevailing in the underwater environment.

2. Visual

The SEALAB II report also includes descriptions of water visibility measurements, both physical and psychophysical (Ref. 9, pp. 250-51). A device for measuring water clarity, developed by Scripps Institution, is briefly described (p. 251). A program for measuring aquanauts' visual acuity underwater and an experiment for the detection and identification of 10 stationary visual targets, rectangular in shape and painted various colors as well as black and white, to be set at various distances and viewed from inside the habitat, are described under the heading UNCOMPLETED STUDIES (p. 253). However, a study of target form and color visibility at the bottom was carried to completion (p. 251); results reported (p. 261, Table 30) show that a black circle 707 square centimeters in area was detected and recognized with significantly higher accuracy than the other three targets used: a 900 square centimeter white square, a yellow triangle, and a white cross.

Underwater visual perception problems received increased attention following completion of SEALAB II in late 1965. The Navy's Submarine Medical Center has investigated a number of problems in areas delineated by Pauli and Clapper;[9] during the present study, several research reports were acquired from that Center. They deal with basic problems of human ability to see in the underwater environment. One of these--the estimation of size and distance of unfamiliar objects[17]--concluded that object size tends to be overestimated with increasing distance, both in air and in water (visual cues normally present were deleted as an experimental control), and also that in unstructured (i.e., cue-poor) visual fields estimates of distance between observer and object generally exceed the true distance. In another experiment[18] it was shown that viewers' ability to resolve standard targets (Landolt Rings) was better under water than on the surface (distances being identical for both conditions and apparant luminances being equated). Viewers wore SCUBA masks in both situations. Kinney, Luria, and Weitzman[19] examined the visibility of various colors, both fluorescent and nonfluorescent, in four different bodies of

water, ranging in clarity from very murky to clear. Targets were observed both by SCUBA divers underwater and by subjects on the surface looking down vertically. Fluorescent colors were found to be consistently more visible than nonfluorescent, but the visibility of specific colors depended on light-transmission properties of the water. The significance of this study, from both theoretical and applicational points of view, lies in the careful measurements taken of total and spectral transmittance of water at the four test locations and in the development of a psychophysical color confusion-matrix based on observers' judgments of all targets under all conditions. Luminance and chromaticity were specified for samples of all paints applied to targets used in the experiments.

In another study of color perception derived from reports by SEALAB aquanauts, Kinney and Cooper[20] simulated in the laboratory the homochromatic characteristics of underwater visual environments. Observers adapted during the procedure to constant-luminance visual fields of white, blue-green, and (for control purposes) red illumination and then made judgments on the color appearance of objects displayed within the fields. In a related procedure, subjects adapted to each of the three homochromatic fields, then were given detection-time tests of the colored objects previously used. The amount of change in the appearance of colors was highly significant, ". . . easily accounting for the reports of SEALAB divers who said they could see yellows and reds when there were none present. There was however no change in the subjects' speed of reacting to the colors."

To examine the notion that contextual cues may be related to the visual perception of depth, Luria, Kinney, and Weissman[21] performed laboratory experiments investigating the nature of the "filled-unfilled space" illusion. They concluded that, when there was a clear contextual connection between the observer's viewpoint and a "standard" or reference object with which another ("variable") had to be compared, the standard and variable objects appeared to be closer together than when the connection was absent. Observers viewed the test objects with both eyes and one eye at various times; it was concluded that the results of the experiment could not be attributed to stereoscopic visual effects.

Luria[22] studied the ability of divers to equate the distances of objects underwater. In the first of three experiments, he tested stereoacuity (visual judgment of relative distances of objects) in air and in water, finding that viewing the depth-perception apparatus through approximately 16 feet of water degraded stereoacuity by a factor of 4 compared with viewing over the same distance from the surface. In the second experiment, the effect of water clarity on stereoacuity was studied at four levels of light-transmissability. It was found that relative

depth-perception deteriorates as water clarity decreases and that depth-perception becomes more variable. A third experiment was run to test the effect of the loss of part of the peripheral field on foveal (central) stereoacuity, by reducing the visual angle for each eye to 10^{o} with special goggles; this time the observers viewed the test apparatus in air to isolate the water effect. It was found that restricting the field of view did not produce the overall degradation produced by viewing through water, although observers were about as variable as before. Taking the results of the three experiments together, it was concluded that the loss of stereoacuity underwater is a function of two possibly interacting variables: water clarity and peripheral visual cues.

Weltman, Christianson, and Egstrom[23] investigated the effects of five different face-masks worn by SCUBA divers on the angular size of the visual field available. They found that all five masks permitted practically full use of the upper field (limited only by divers' eyebrows), but that they all imposed considerable restriction on side visibility; "however, quite a large useful area remained." The three standard partial-masks used in the study imposed severe limitation of lower-quadrant visibility, and are considered by the authors to be detrimental in underwater search tasks or work with equipment at very close range. It was concluded that the full-face mask--despite the problem of supplying air without impairing vision--provided the diver with the most effective seeing capability under water. A novel visual perimetry apparatus is described, as developed for use in these experiments.

Andersen[24] reports experiments conducted in the Bahamas, in the open ocean, comparing the visual search capabilities of SCUBA divers and submersible vessel operators in locating and identifying targets laid out along a linear course and presented to observers at three viewing distances. The working depth was 55 feet, visibility was 50 feet, and the submersible vessel was operated over the course at three different speeds. The test targets were designed to combine three forms (square, triangle, circle) with five colors (black, red, yellow, blue, and green). Each of three subjects served both as SCUBA diver-observer and as vehicle operator-observer (STAR II was the vehicle used). The conclusion reached was that there were ". . . no significant differences in the ability of SCUBA divers and submersible operators to discriminate color and form or in their visual acuity." The author notes that vehicle operators confused red targets with blue or green, while SCUBA divers consistently confused red with black. From his discussion, it appears that Andersen concludes that black and green were also highly confusable under the conditions of his study, but that blue and yellow were easily distinguishable and very accurately identified, regardless of viewing distance.

While not primarily concerned with vision as an independent variable, the experiments of Weltman and Egstrom[15] on perceptual narrowing are relevant to a consideration of the effects of the underwater environment on divers' seeing ability. Although their results were anything but strongly conclusive, they contain a suggestion, underscored by the more definitive work of others (see for example MacInnis, 25), that heightened levels of anxiety can reduce divers' ability to sense events occurring at or near the edge of their fields of vision while they are concentrating on a fairly demanding task.

3. Tactile

The Mackworth V test has been widely used to measure the effects of water-temperature on divers' finger numbness, in terms of tactile discrimination. Bowen and Pepler[1] obtained tactile-discrimination threshold data on four subjects, first on land then after 12 minutes' exposure to five water temperatures ranging from 70° downward to 44°F and found systematic, significant increase in threshold as water-temperature decreased. They noted that this probably accounted in part for deterioration of performance underwater where fine dexterity is called for. Stang's results[3] agree, in fact showing finger sensitivity deteriorating by better than 50% when divers are subjected to 50°F water temperature for 90 minutes, compared with sensitivity at 70°F for the same length of time. Both Bowen and Pepler and Stang interpret these findings as explaining divers' difficulty in handling small objects during underwater assembly work; Bowen and Pepler note that their divers reported that as their fingers became increasingly numb, they had to pay closer visual attention to their work, diverting attention from routine checking of personal equipment and other necessary operations.

Baddeley[8] administered the V test to diver subjects on dry land and at two underwater depths in open sea (10 and 100 feet), primarily to assess effects of nitrogen narcosis on tactile sensitivity; he found no significant change in threshold with depth. Water temperatures encountered during his experiments were not reported.

D. Communications

Since relevant literature considered during this project related only to voice communication under actual or simulated underwater conditions, the following review will discuss only that mode. As previously noted in the discussion of auditory perception, the Project SEALAB II Report described aquanauts' observations of speech under hyperbaric (200 foot) HeO_2 atmosphere, but reported no quantitative findings. Most

of the available publications originated at the research laboratories of the Navy Submarine Medical Center, located at the Submarine Base, New London, Connecticut.

One of the earliest systematic investigations of the effect of HeO_2 atmosphere on speech was reported in 1962 by Beil.[26] He had four male speakers inhale pure medical helium, then repeatedly utter each of six English vowel sounds; for each speaker 12 repetitions under helium and 8 under normal air (for comparison purposes) were recorded for detailed spectral analysis. It was shown that an increase occurred in the component frequencies of each vowel sound, but that the ratios between formants remained nearly constant. Sergeant[27] made formal word- and sentence-list intelligibility measurements on the speech of two male subjects prior to and during a 144-hour HeO_2 test-chamber experiment at atmospheric pressure. He found that during the first two days, speech-intelligibility deteriorated significantly, but then improved, returning almost to normal by the end of four days; this was interpreted as evidence of an adaptive process in the talker. This finding supports the anecdotal data collected during SEALAB II in which aquanauts stated that they observed adaptation occurring among themselves as their 15-day submergence periods proceeded, specifically mentioning a lowering of voice-pitch and slowing-down of speaking rate. (Sergeant did not undertake to explain the mechanism of adaptation revealed by his data.)

In a somewhat later paper, Sergeant[28,29] reported the results of intelligibility and acoustic-spectrum measurements on the speech of five Navy divers breathing 81% He-19% O_2 at atmospheric pressure, confirming the earlier finding of decreased intelligibility. He noted that although voice quality changed drastically, the fundamental voice frequency did not shift appreciably and could be maintained at or near a given level by conscious effort on the part of the speaker. He calculated that the formant frequencies, related to changes in resonant characteristics of the cavities above the vocal folds themselves, shifted upward by an average ratio of 1.51, compared with normal-air frequencies.

In an attempt to improve the intelligibility of helium speech, Sergeant[30] experimented with a variety of passband filters through which tape-recorded samples of HeO_2 and air speech had been processed. He came to the conclusion that no condition of filtering would increase helium speech intelligibility as compared with the no-filter condition.*

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* It is not clear why Sergeant chose to attack the problem of HeO_2 speech-intelligibility restoration in this way, because passive filtering as he employed it, does not counteract the upward frequency shift he had discovered in the experiment discussed previously.

In England, Holywell and Harvey[31] made detailed measurements of the fundamental and formant frequencies of speech uttered by speakers breathing air and again HeO_2, at both normal atmospheric and four-atmosphere pressures. In addition to confirming Sergeant's formant frequency-shift in HeO_2 of 1.5 times the air frequency at normal pressure, they showed that four-atmosphere air produced an upward shift in formant frequencies (compared with normal pressure air), and a slight shift upward in the voice fundamental. This pressure-induced shift occurred only when air was the breathing gas; helium under four-atmosphere pressure seemed not to produce a greater shift than it did at normal pressure. They further experimented with a simple technique to improve intelligibility of helium speech by restoring it to its original frequencies--playing back tape recordings at reduced speed. An average improvement of almost tenfold was reported.

Brubaker and Wurst[32] studied the effects of HeO_2 at simulated depths down to 300 feet on spectra of speech sounds, generally corroborating Holywell and Harvey with respect to the He-induced formant shifts. Additionally, they noted that at 300 feet, vocal frequencies were 0.5 to 0.6 octave higher than at surface pressure. The authors interpreted this response to indicate increased vocal effort on the part of the speakers, in response to the effects of increased pressure on air-conduction hearing and therefore on the speakers' evaluations of their own vocal output.

Gerstman, Gamertsfelder, and Goldberger[33] reported the effects on speech-formant frequencies of various pressures and compositions of HeO_2 mixtures, concluding that the relationships were sufficiently complex as to render restoration of original intelligibility by instrumental means complicated and costly, with reasonable approximation the most practical goal. (The paper, incidentally, is an expansion and informalization of a much more compressed presentation given before the Acoustical Society of America at its 72nd meeting in Los Angeles, November 1966.)

More recently, Sergeant[34] constructed a confusion matrix for English consonants from experimental data as a first step in establishing a rationale for predicting intelligibilities of special vocabularies that might be designed for use by HeO_2-breathing divers. All data were obtained from four speakers breathing 80% He-20% O_2 at normal atmospheric pressure. It was concluded that ". . . there is a marked similarity between helium speech and speech in air when intelligibility according to linguistic classification is observed. However, unaccountable differences do exist between the two breathing media for ranked intelligibilities of specific consonants."

In a paper given before a recent meeting of the Instrument Society of America, Sergeant[35] reviewed the known and probable causes of speech-communication distortions in deep diving; this paper presents no original data, but does provide a useful tutorial overview of certain fundamentals of speech production as well as practical considerations imposed by the deep-submergence environment (down to 1,000 feet).

In connection with developmental techniques for restoring intelligibility to helium speech at a simulated depth of 400 feet (13.13 ata), Sergeant[36] utilized a "high fidelity" (characteristics otherwise not described) system for tape recording standard intelligibility word lists read by an experienced diver in an atmosphere consisting of 88% helium, 6% nitrogen, and 6% oxygen. When played back at original recording speed (formant frequencies uncorrected for helium shift), 78.0% intelligibility was obtained; when playback speed was reduced to one-half normal speed, intelligibility rose to 96.8%. It was noted that voice quality under this latter technique was quite different, but that distortions were evidently introduced to the detriment of recognition of the speaker's voice. A second technique was tried (the Varivox tape-playback, consisting of counter-rotating tape transport and pickup head assembly) and yielded intelligibility of 85.6%, which was interpreted by the author as "significant."

In a paper to be published as a chapter in a medically oriented book on diving and performance under hyperbaric atmospheres, Sergeant[37] reviews current knowledge regarding speech communication, pressure, and atmospheric composition, and examines the efficacy of several corrective or "speech unscrambling" techniques. This paper makes no attempt to report new findings, but summarizes adequately material compiled from widely disparate sources.[38]

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Appendix C

REVIEW OF THE PERFORMANCE CAPABILITIES OF MECHANICAL MANIPULATORS

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A. Underwater Mechanical Manipulator Design Considerations

Present-day mechanical manipulators may be categorized as follows:

- Mechanical master-slave type, which duplicates the motions of the operator's hand by means of a purely mechanical linkage. Feedback is transmitted back through the linkage, and sensitivity of feedback is proportional to the inertia of the system.

- Servomanipulator, or powered master-slave type, which duplicates the motions of the operator's hand by means of proportional control links, either electrical or hydraulic.

- Rate-controlled, powered manipulator type, which is operated by an open-loop control system and actuated by on-off switches with provision for rate control. Feedback is visual only.

The mechanical master-slave is the manipulator used in most nuclear installations. Its virtues are high reliability, ease of use, and good dexterity; feedback is automatically supplied through the mechanical linkage. The servomanipulator has the dexterity and ease of use of the mechanical master-slave and has the benefit of complete mechanical separation of the operator and the manipulator. Unfortunately, the requirement for feedback control imposes such complexity on the system that this type of manipulator has not yet achieved the degree of reliability desired even for land operation.

Neither of the above two classes of manipulators appears practical for undersea use. The master-slave concept of the two manipulators requires that the operator have the capability of complete arm swing, which is a space luxury that usually cannot be afforded in the deep submersible. The mechanical master-slave also is infeasible because of the need for penetration of the pressure hull with mechanical linkages, which is difficult at extreme depths. The servomanipulator does not require such hull penetrations, but as noted above such manipulators are currently too complex and unreliable for undersea use.

For these reasons, all of the manipulators currently in use in submersible vehicles appear to be either fixed or variable rate-controlled, powered manipulators. Many have small, portable control boxes that may be carried by the operator to the viewport affording the best visual control of the task. Although feedback is primarily visual, suggested aids include a device for indicating the grip force being exerted by the manipulator terminal device and a small hydrophone mounted near the manipulator arm to transmit the sounds of striking small objects. Of course, visual feedback may be obtained directly or by means of periscope or television.

One manipulator arm would seem to suffice for most oceanographic missions, but it appears that two arms are necessary if the submersible is to perform meaningful work. The arms are spot-mounted on the hull, and it appears that the most efficient arm configuration is one resembling the human arm (that is, with universal joints corresponding to the human wrist and shoulder and another joint corresponding to the human elbow).

It is generally recognized that, to be at all efficient underwater, a work boat must have the capability of exchanging terminal devices on the manipulator arm. Although the choice and design of terminal devices to be carried will depend to a great extent on the particular mission, in general this capability is preferable to using an "all-purpose" terminal device to hold and actuate a separate tool, as has been the previous practice. Such a capability allows the tool to be mechanically coupled to a motor
with an impact wrench or drill chuck), avoiding the necessity of either using self-powered tools or having trailing electrical or hydraulic connections to the tool.

Some of the considerations that must be taken into account in designing mechanical manipulators for undersea use are as follows:

- <u>Hydrostatic pressure</u>

  As mentioned previously, this factor imposes limitations on pressure hull penetrations and, hence, on mechanical linkages. It also affects the design of hydraulic control lines, which must usually be pressure compensating in some way.

- Corrosion and conduction

  The corroding action of seawater has played havoc with some of the early manipulator models, especially affecting fastenings and castings and spots where the surface of the manipulator arm had been scraped. Most manipulators are now being made from stainless steel, but still may suffer from corrosion if left in the water for prolonged periods without maintenance. The high electrical conduction of seawater requires rigid insulation standards for all electrical lines and motors used in the manipulator.

- Visibility

  Frequent conditions of reduced visibility limit the effective lengths of the manipulator arm. A six-foot arm reach seems to be about the maximum useable under normal conditions, although a 12-foot arm has been recommended for a vehicle that will have to support heavy objects (however, it was noted that the full 12-foot extension may frequently be of no use because of the poor visibility conditions that can be expected). Even though visibility may be sufficient to carry out the task, the loss of detail, and especially of perspective, may be sufficient to affect severely the time required for task completion.

- Relative motion

  Excessive motion between the vehicle and the object to be manipulated can make effective manipulation difficult, if not impossible. The vehicle to which the manipulator is attached must supply gross positioning ability; but most vehicles cannot maneuver to the 1/4- or 1/2-inch positioning requirements of many remote handling tasks and hence cannot be used for fine positioning. Rather the vehicle must provide a stable platform, through grappling onto the object to be manipulated, using auxiliary anchoring systems, trim systems, and the like. According to studies conducted at North American Rockwell, the maximum tolerable rate of motion between the outstretched manipulator arm and the object to be manipulated is 4 inches per second.

A 50-pound capacity seems to be the nominal value for manipulator arms on work boats (where capacity is defined as the force that the outstretched arm can exert in any direction). Some manipulators designed for heavy salvage work have capacities up to 500 pounds, but a 50-pound capacity is enough to enable the manipulator to handle tools of a size that a man would have to use two arms to support. In general, larger

capacity arms carry with them the burdens of increased clumsiness and problems in maintaining a stable platform with the vehicle.

B. Underwater Mechanical Manipulator Characteristics

A comprehensive study of tasks to be performed by five deep submergence vehicles established the required characteristics of mechanical manipulators.[1] The following vehicles were considered.

1. AUTEC Vehicle

The AUTEC is a relatively small vehicle intended for use with the AUTEC program. It is to be capable of assisting in salvage operations to a depth of 6,500 feet. It also must be able to inspect, test, retrieve, and place electronic systems on the ocean bottom, as well as to perform other oceanographic operations.

2. Deep Submergence Rescue Vehicle (DSRV)

The primary mission of the DSRV is to rescue personnel from disabled submarines. The designs specify operations to a depth of 9,000 feet, with visibility limited to 3 feet. The vehicle is to mate with a disabled submarine and shuttle personnel in groups of 12 to a surface ship or another submarine.

3. Oceanographic Submarine (NR-1)

The NR-1 is a large research submersible capable of extended cruising. Manipulators would be used for such tasks as exploring the continental shelves and maintenance of equipment, search, and recovery on the ocean floor.

4. Trieste III

The Trieste III is a bathyscaph similar to Trieste II; its primary mission is to reach great ocean depths, to 20,000 feet and to observe conditions on the ocean floor.

5. Deep Submergence Search Vehicle (DSSV)

The DSSV is designed to operate at cruising speed over fairly large distances, carrying a crew of 3 to depths of 20,000 feet. It will recover and transport objects weighing up to 150 pounds from its design depth and will assist in salvage at depths to 2,000 feet.

The manipulators proposed for vehicles 1, 2, 4, and 5 are identical in specifications; the manipulator proposed for vehicle 3 is essentially a larger version of the same manipulator. In the following summary, specifications will be given for the smaller manipulator and specifications for the large manipulator of vehicle 3 will be shown in parentheses if they differ.

- Reach

  Minimum active length 72 inches (144 inches)
  Maximum retracted length 36 inches (72 inches)

- Capacity

  Minimum wrist-roll torque 1,500 inches per pound (10,000 inches per pound)
  Minimum force exertable in any direction 50 pounds (250 pounds)

  The small manipulator should also be able to exert a 600-pound force in the horizontal direction 3 feet below the shoulder axis.

- Degree of freedom

  Each manipulator should have 7 degrees of freedom, each controlled by a separate actuator. There is to be no visible backlash, nor any visible overshoot resulting from the motion of starting or stopping the manipulator.

- Motion rates

  Range of shoulder vertical, horizontal, and elbow motion 1/2 inch per second to 8 inches per second.

  Range of wrist vertical, horizontal, and extend motion 1/4 inch per second to 4 inches per second.

  Range of wrist rotate motion 1/2 rpm to 8 rpm.

- Motion locking

  Each of the above motions should hold its position when the manipulator is not in action. Tolerated motion drift is not to exceed 1/16 inch per minute with full rated load (cumulative over all motions).

- <u>High force terminal device actuator</u>

  Maximum grip force provided, 2,000 pounds through 4-inch stroke (8,000 pounds through 8-inch stroke)

  Range of controllable grip force, 100-2,000 pounds (400-8,000 pounds)

  Accuracy of controllable grip force, ± 20%

- <u>High speed terminal device actuator</u>

  Range of drive speed, 400-3,450 rpm
  Maximum torque, 30 inches per pound (300 inches per pound)

The following terminal devices may be positioned at the end of the manipulator and actuated by one of the terminal device actuators:

- <u>Hook hand</u>

  Jaws shaped to fit hexagonal stock and close to zero opening at the center of the grip.

  Maximum grip force, 2,000 pounds (8,000 pounds)
  Maximum opening, 2-1/4 inches (5 inches)
  Stroke, 4 inches (8 inches)

- <u>Parallel jaw hand</u>

  Closes to zero opening; application of full wrist torque will not permanently distort jaw mechanism.

  Maximum grip force, 1,500 pounds (3,000 pounds)
  Maximum opening, 5 inches (10 inches)

- <u>Three-jaw clam shell gripper</u>

  Formed by three orange peel jaws.

  Maximum diameter of object encompassed, 12 inches (16 inches)
  Minimum gap between section when closed, 1/16 inch.

- <u>Prosthetic hand</u>

  Patterned after the split prosthetic hook design.

  Maximum diameter of object grasped, 5 inches (10 inches)
  Maximum grip force at knee of hook, 250 pounds (1,000 pounds)

- Grapple hand

  In planar movement, 2 tines interleave with 1 opposing tine

  Range of diameters gripped firmly, 0 to 12 inches
  Maximum grip force, 250 pounds (1,000 pounds)

- Drill chuck

  Of the standard Jacobs design, but equipped with rotation stops in the outer sleeve.

  Capacity, 0 to 1/2 inche (0 to 1 inch)

- Centrifugal pump

  Used either as suction or jetting device, with nozzles exchanged by divers. The pump should be driven by a high speed terminal device actuator.

- Impact head

  Modification of standard square drive, continuous rotation input type of impact wrench, using the head portion only and relying on the high speed terminal device for actuation.

  Head size, 1/2-inch square (1-inch square)

- Cable cutter

  Capable of shearing a limp stainless steel cable.

  Maximum diameter of cable to be cut, 1 inch (2 inches)

- Stud gun

Thickness of plate to be penetrated, 1/2 inch
Maximum shear or extraction strength of stud, 4,000 pounds

The following remarks are general conclusions reached in the study bearing on the above specifications:

- Since weight is generally a critical factor, the smallest possible manipulator is desirable. About a 6-foot reach is the minimum length to allow reasonable area coverage by the manipulator, and the 6-foot length, 50-pound capacity arm is consistent with the mission and viewing requirements of the smaller vehicles. The size of the arm for the NR-1 is consistent with vehicle size

and mission, although it should be noted that vision may be poor for this large an arm in turbid water.

- In general, manipulators should not be used as cranes or heavy weight lifters, but rather as "riggers." Many manually operated tools can be modified for use with manipulators. A 50-pound manipulator capacity (which is compatible with the 6-foot size manipulator) will be adequate for handling power tools of the type that are normally hand-held and have been modified for underwater use.

- It should be noted that load capacities are specified for the worst arm configurations and that up to double this specified capacity may be handled in more favorable manipulator positions.

- At least 6 degrees of freedom are required if the manipulator is to have full capability of locating and orienting the terminal device. A seventh degree of freedom, wrist extension, is included to speed up many of the manipulator operations.

C. Capabilities of Underwater Mechanical Manipulators

The most satisfactory applications for underwater mechanical manipulators will probably be in tasks related to construction, assembly, or maintenance since these tasks can be specifically engineered and designed to accommodate the shortcomings of mechanical manipulations. Such design considerations should include the following:

- Providing easy access to all nuts, bolts, valves, and the like.
- Minimizing the number of different nut sizes.
- Fitting all nuts with conical heads
- Redesigning clamps and other hardware requiring "two-handed" operation.
- Utilizing nonjammable threads and large access holes in nuts and tapped holes.
- Making nuts and bolts captive so they will not be dropped.

Manipulators may be less useful in nondesignable jobs, such as salvage tasks, where the limited versatility of manipulator tools may not be adequate for the job. However, given enough time, even these jobs can be accomplished by mechanical manipulation with the limits of dexterity and mobility imposed by the vehicle-manipulator system.

The question of how much more time it will take a manipulator to perform a given task compared with the time required for manual performance is still a matter of conjecture. R. C. Goertz, in "Human Factors in Design of Remote Handling Equipment," notes that on dry land a mechanical master-slave manipulator takes 6 to 10 times as long as a man to perform a given task, and as much as 10 times as long for a rate-controlled manipulator compared with a master-slave. Therefore, under shirtsleeve conditions, an undersea manipulator might be as much as 100 times slower than a man in performing a task. However, in the underwater environment, this ratio decreases to a factor of about 10 when compared with a shallow-depth SCUBA diver and equals and finally surpasses a hard-hat diver at his marginal depths.

Unfortunately, actual experience in underwater mechanical manipulation at present is so limited that the above remarks can be considered to be only educated guesses. It appears that this question will be partly answered by the performance of the Beaver Mark IV vehicle, to be launched soon by North American Rockwell. Since the Beaver is the first submersible to be designed as a work boat from the keel up, the performance of this vehicle in actual underwater tasks will yield a state-of-the-art comparison between the underwater capabilities of man and those of mechanical manipulators. So far, no information on the performance of the Beaver manipulator is available, but several facts seem fairly evident from the brief view of the vehicle and of a film clip of manipulator tests:

- The manipulator movements are rate-controlled by the operator, but it is not known which controls the operator uses to control the manipulator or what feedback considerations may have been added to supplement those obtained visually.

- Fine positioning capability of the manipulator arm, as shown on the demonstration film, seemed limited effectively to motions on the order of 1 to 1/2 inch, with overall manipulative capability generally quite clumsy. Although satisfactory alignment of such tools as drill chucks, stud guns, and impact wrenches may simply be a matter of taking enough time, the manipulator seems unsuited for work requiring any appreciable degree of "dexterity." Complicated patterns of wrist movement appear to be extremely time consuming to perform with the manipulator, and of course the manipulator is totally incapable of "finger work"--i.e., those tasks involving such small and precise movements that a human would perform them with his fingers with wrist fixed.

- The operators of the manipulator seem to have much trouble with perspective and with the orientation of the terminal device in the desired geometrical relationship with the object to be worked on. For example, in using a stud gun the operator had great difficulty in placing the gun perpendicular to the surface, sometimes being in error by as much as 30 degrees.

Thus, all signs seem to indicate that current undersea mechanical manipulators may minimize the need for man, but they certainly cannot replace him. The manipulators are built on too gross a scale to accomplish jobs requiring fine dexterity or precision, so at least for the present man must be available to accomplish such jobs. Although the manipulators will probably outperform man in tasks requiring the use of the powered terminal devices, such as the impact wrench, we have yet to see whether manipulators will be capable of using the general purpose hands to effectively use other hand tools that may occasionally be needed.

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13. ABSTRACT

Naval undersea missions and operations in the 1975-1985 time frame that require the use of MAN-IN-THE-SEA concepts are delineated. The MAN-IN-THE-SEA concept is broadly defined in this study to include all undersea systems requiring man's exposure to the ambient ocean pressure. MAN-IN-THE-SEA missions and operations within the overall spectrum of naval undersea missions and operations are isolated on the basis of comparisons of functional performance capabilities of alternative systems. The functional requirements related to the naval undersea missions and operations, together with the isolated MAN-IN-THE-SEA missions and operations, are initial results of a continuing study of naval applications of MAN-IN-THE-SEA concepts.

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